แผ่นกรองไหมไฟโบรอินเพื่อกำจัดอนุภาคมลสารในอากาศภายในอาคาร

นางสาว จันทร์จิรา ตรีเพชร

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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SILK FIBROIN FIBER FOR INDOOR AIR PARTICULATE MATTER REMOVAL

Miss Janjira Triped

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งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาการสังเคราะห์แผ่นกรองไหมไฟโบรอิน (SF) สำหรับการกำจัดอนุภาคมลสารในอากาศในอาคาร โดยสังเคราะห์แผ่นกรอง SF จากการดีกรัมรังไหมด้วยโซเดียมคาร์บอเนต (0.5 wt % Na_2CO_3) ในการทดลองนี้ได้ศึกษาลักษณะ วิเคราะห์สมบัติทางกายภาพ และสมบัติทางจลนพลศาสตร์ของแผ่นกรองไหมไฟโบรอิน (SF) ในการทดลองนี้ได้ทำการศึกษาผลของอัตราการดูดอากาศ ความเข้มข้นเริ่มต้นของอนุภาคมลสาร และผลของแผ่นกรองที่ชนิดต่างๆกัน ที่มีผลต่อการศึกษาเปรียบเทียบประสิทธิภาพการกรองอนุภาคมลสารในอากาศ โดยใช้รำข้าวจากโรงสีข้าวชุมชนภายในจังหวัดอุบลราชธานี เป็นอนุภาคมลสารในอากาศภายในอาคาร

จากการทดลองเมื่อทำการศึกษาลักษณะและสมบัติทางกายภาพด้วยกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราดพบอนุภาคบนแผ่นกรองกรองไหม SF มีขนาดรูพรุนเป็นแบบมีโซพอเท่ากับ 24.664 ± 0.005 Å และมีค่าการทนแรงดึงเฉลี่ยเท่ากับ0.024±0.008 นิวตัน/ตารางเมตร แผ่นกรองไหม SF มีประสิทธิภาพการกรองสูงสุดร้อยละ 70.39±0.68 และ 37.85 ± 3.04 สำหรับ PM_{10} และ $PM_{2.5}$ ตามลำดับ ที่อัตราการดูดอากาศ 5 ลิตร/นาที รวมทั้งพบว่าเมื่อเพิ่มความเข้มข้นเป็น 2, 3, 4 และ 5 เท่า จากความเข้มข้นเดิม สำหรับ PM_{10} มีประสิทธิภาพการกรองสูงสุดร้อยละ 70.39±0.68 เมื่อใช้ความเข้มข้นเริ่มต้นที่ 0.040 มล./ลบ.ม. สำหรับ $PM_{2.5}$ มีประสิทธิภาพการกรองสูงสุดร้อยละ 57.26±3.36 เมื่อใช้ความเข้มข้นเริ่มต้นเป็น 0.080 มล./ลบ.ม. และจากการเปรียบเทียบประสิทธิภาพการกรองของแผ่นกรองต่างชนิดกัน พบว่าแผ่นกรอง 3M-8210 มีประสิทธิภาพการกรองสูงสุด และพบว่าแผ่นกรองไหม SF มีราคาถูกกว่า แผ่นกรอง 3M-8210 ถึง 10.7 เท่า ดังนั้นจึงควรใช้เป็นทางเลือกในการบำบัดอากาศภายในอาคาร

สาขาวิชา การจัดการสิ่งแวดล้อม ลายมือชื่อนิสิต..
ปีการศึกษา 2008 ลายมือชื่อ อ.ที่ปรึกษาที่ปรึกษาวิทยานิพนธ์หลัก ....
ลายมือชื่อ อ.ที่ปรึกษาที่ปรึกษาวิทยานิพนธ์ร่วม ....

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KEY WORD: INDOOR AIR/ PARTICULATE MATTER/ SCANNING ELECTRON MICROSCOPE (SEM)/ SILK FIBROIN FIBER

JANJIRA TRIPED : SILK FIBROIN FIBER FOR INDOOR AIR PARTICULATE MATTER REMOVAL
THESIS ADVISOR: ASSIST. PROF. WIPADA SANONGRAJ, THESIS CO-ADVISOR ASSIST. PROF. BOVORNLAK OONKHANOND, 113 pp.

The main objective of this research is to synthesize silk fibroin fiber for indoor air particulate removal. Silk cocoons were de-gummed using 0.5 wt % Na_2CO_3. In this work, the morphologies, physical properties, and mechanical properties of the SF fiber were studied Three sets of experiment were conducted to investigate the impacts of air flow rate, initial particulate matter (PM) concentration, and that of filter types on the PM removal efficiency. Rice bran collected from a local rice mill in Ubonratchathani province was used as indoor air contaminant in this work.

The SEM revealed the deposition of PM on the used fiber. The pore size of the SF fiber was estimated to be 24.664 ± 0.005 Å and was classified as mesopore. The mechanical property of 0.024±0.008 N/mm^2 was obtained of the SF fiber. The maximum PM removal efficiencies of 70.39±0.68 % and 37.85 ± 3.04 % were obtained of PM_{10} and $PM_{2.5}$ respectively, when using air flow rate of 5 L/min. When the initial PM concentrations of PM_{10} and $PM_{2.5}$ were increased to 2, 3, 4, and 5 times of the original concentrations, The highest PM_{10} removal efficiencies of 70.39±0.68 % was obtained when using initial concentration at 0.040 mg/m^3. The highest $PM_{2.5}$ removal efficiency of 57.26±3.36 % was obtained when using initial concentration at 0.080 mg/m^3. The effects of different filter types were also included in this study. The results show that the 3M-8210 fiber yielded the highest PM removal efficiency as compared to the SF fiber. However, the SF fiber costs about eleven times less than the 3M-8210. Therefore, the SF fiber could be applied as an alternative material for indoor air treatment.

Field of study: ENVIRONMENTAL MANAGEMENT Student's signature..............................

Academic year: 2008 Advisor's signature..............................

Co-advisor's signature..............................

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LIST OF ABBREVIATIONS

^0C	Celsius
cc	Cubic Centimeter
cm	Centimeter
g	Gram
µm	Microgram
m^3	Cubic Meter
mg	Miligram
min	Minute
mm	Milimeter
m^2	Square Meter
PM_{10}	Particulate Matter Less Than 10 µm
$PM_{2.5}$	Particulate Matter Less Than 2.5 µm

CHAPTER I

INTRODUCTION

1.1 Statement of problem

Indoor air quality has received immense attention in the early 1990s. This is because studies (Jones, 1999) showed that the level of pollutants in indoor environments is actually higher than in outdoor environments. In addition, people generally spend more than 80% of their times in indoors, which contributes a higher risk from inhalation of pollutants than outdoors (Robinson and Nelson, 1995). In 1995, USEPA identified indoor air pollution is one of the top environmental risk (USEPA, 1995). Indoor air pollutants consist of both gaseous and particulate matters. The main objective of this research is to synthesize the SF fiber form silk cocoons for indoor air particulate matter removal. The investigation of the efficiency of the fiber is also included in this work. Particle pollution, also called particulate matter or PM, is a mixture of microscopic solids and liquid droplets suspended in air. This pollution, also known as particulate matter, is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (such as fragments of pollen or mold spores). Sources of particulate matter can be man made or natural. Some particulates occur naturally, originating from volcanoes, dust storms, forest and grassland fires, living vegetation, and sea spray.

One of the major sources of indoor air particles is rice mills particularly from a rice milling process (Sumanno, S., 2007). In Thailand have more industrializations of rice mill, especially in Ubonratchatani province rice mill has therefore caught the interest not only of scientists, but of the general public as well. The total invest industrialization in Ubonratchatani province are 3,951 factories, total investment 12,104,654 millions baht and employment 15,502 persons .The most investitive industrialization is rice mill , these have 3,951 factories and also equally 78.23% of total factory.

Particle exposure can lead to a variety of health effects. For example, numerous studies link particle levels to increased hospital admissions and emergency room visits and even to death from heart or lung diseases. Both long- term and short-term particle exposures have been linked to health problems.

In conventional indoor air particulate matter removal, In general, three methods are suggested to improve indoor air quality, namely source control, increase ventilation and air cleaning. Source control is often ungovernable and unavoidable in metropolis. For instance, vehicular exhaust from nearby traffic, building materials and the use of cooking utensils were inevitable sources of indoor air pollutants (Ao, C.H. and Lee, S.C., 2005). Especially, indoor air quality in rice mill is affected by milling process activities, as well as particularly frying rice mill is among the most important sources of particles indoors air.

Sumanno, S., 2007 had assessed the risk and health impact of workers in the rice mill factories due to noise and particulate matter pollutions. Total of 23 districts in Ubonratchathani province was the case studies. The study included the measurement of noise level and air quality sampling caused by mill process during April 2006 to March 2007. Results from air quality monitoring showed that the 95th percentile of the concentrations were 0.117 mg/m^3 and 0.0366 mg/m^3 for total dust and respirable dust, respectively (Sumanno, S., 2007)

Increase ventilation might even transport more pollutants from outdoor environment (Jones, 1999). Thus, air cleaning remains to be the most feasible option to improve indoor air quality. In indoor air removal of particulate matter many fibrous filters are widely used for air cleaning system, such as activated carbon fiber (ACF) filter. Researchers had used of its, focusing on the improvement of its particle collection efficiency by using electrostatic charge caused by surface modification with chemicals and enhancement of adsorption capacity by chemical impregnation. (Otani, Y. *et al.*,1991). However, the usage of activated carbon fiber (ACF) filter is changed by treatment of chemical with hydrogenperoxide (H_2O_2) has been treated at different conditions that hardly treated ACF filter.

One of the fibrous filters is silk fibroin fiber from silkworm. Recently regenerated silk solutions have been used to form a variety of biomaterials, such as gels, sponges and films, for medical applications. (Chen, C. *et al.*, 2006). The electrospun silk fibroin (SF) fibers, with high specific surface area, high porosity and good biocompatibility, have extensive applications in the field of biomaterials, such as tissue scaffolds and drug delivery. Electrospinning is an attractive method of producing fibers with diameters ranging from micrometers down to tens of nanometers. Silk fibroin has been electrospun with the spinning solvents such as hexafluoro-2-propanol (HFIP), hexafluoroacetone (HFA) and formic acid or in combination with PEO. *B. mori* silk could be electrospun as a blend with PEO from aqueous solutions and then they obtained silk/PEO fibers with core/shell structure. Recently, silk fibroin aqueous solutions from de-gummed *B. mori* silk or *B. mori* gland have been used to prepare silk fibers and the fibers with submicron diameter were successfully obtained (Jingxin, Z., *et al.*, 2008). Studies on both silkworm and spider have indicated that several physiological parameters, such as water content, pH, shear rate and elongational flow, are thought to be very important in the natural spinning process.

Magoshi *et al.*, found that when the silk dope flows from the posterior division to the anterior division of a silk gland of silkworm, it has a decrease in water content from 88 to 70 wt% and a decrease in pH from 6.9 to 4.8. The conformation of the silk dope is also thought to be transformed from the predominant random coil into liquid crystalline β-sheets. Spinning dope then undergoes elongation at a rate of 500 mm/min through small spinnerets to form water insoluble fiber in air (Magoshi, J., *et al.*, 1996), and Chang Seok Ki *et al.*, found that electrospinning silk fibroin had investigated that silk fibroin and wool keratose/silk fibroin blend nanofibrous membranes were prepared by electrospinning and their performances were evaluated as a heavy metal ion adsorbent (Chang, S. K., *et al*., 2007) .

Allthought electrospinning is an attractive method of producing silk fibers with diameters ranging from micrometers down to tens of nanometers,but must controls several physiological parameters, such as water content, pH, shear rate, elongational flow, expensively and also they may be insufficiently wettable or wickable; their fine fibers may lead to a weak web strength in electrospun process.

The basic preparation of silk fibroin de-gummed that silk fibroin is purified from via boiling in alkaline solution. Cocoons of the *Bombyx mori* silkworm had degummed with sodium carbonate (Na_2CO_3) solution and washed with warm distilled water to remove the sericin, then dried at room temperature. (Chen, C., *et al*., 2006). The de-gummed or purified silk fibers can be processed into non-woven mats. Bao Zhong Tian *et al*. found that the adsorption filtration capacity of de-gummed with 0.05% W/V Na_2CO_3 of *Bombyx mori* silkworm silk fibers (dSSFs) against mainstream smoke (MS) substances. Through the blocking and filtering of dSSF filter tip, the total content of polycyclic aromatic hydrocarbon compounds (PAHs) of cigarette MS decreases greatly, compared with through cellulose diacetate (CDA) filter tip. When the filling mass is equal to, or larger than 50 mg per filter tip, the amount of MS substances adsorbed by dSSF filter tip is close to or greater than by commercial CDA filter tip with the filling mass of 130 mg. The results can provide a guideline for designing or developing a new kind of cigarette filter tips or new adsorption filtration materials using silkworm silk fibers (Bao, Z. T., *et al*., 2008).

This research study will use preparation of silk fibroin fiber from cocoons of the *Bombyx mori* silkworm were de-gummed with sodium carbonate (Na_2CO_3) solution. In the present study, the ability of silk fibroin as a fiber for filtration of particulate will be investigated by Side Pak Personal Aerosol Monitor.

1.2 Objectives

The main objective of this study is to synthesize silk fibroin (SF) fiber for indoor air particulate matter removal. In order to achieve the goal, we have divided the main objective into two sub-objectives as follows:

1. To synthesize the SF fiber from silkworm by de-gumming with alkaline solution.
2. To study the characterization and mechanical properties of the SF fiber.
3. To investigate the efficiency of SF fiber for indoor air particulate removal.
4. To compare the efficiency of SF fiber and that of the commercial fiber for indoor air particulate removal.

1.3 Hypothesis

Effective fiber for indoor air particulate matter removal could be readily prepared by degumming silk cocoons in 0.5 wt % Na_2CO_3.

1.4 Scope of study

The research is divided into four phases as follows:

Phase 1: The preparation of silk fibroin fiber.

The SF fiber form silk cocoon was de-gummed by boiling them in 0.5% (w/w) Na_2CO_3 for sericin extraction. The initial concentrations of indoor air particle were maintained at 0.040 ± 0.005 mg/m^3 and 0.020 ± 0.005 mg/m^3 for PM_{10} and $PM_{2.5}$, respectively. PM concentration was measured by the Side Pak Personal Aerosol Monitor (AM 510).

Phase 2: The efficiency of particle removal by silk fibroin fiber.

The SF fiber was used as a filter for filtration during 8-hour. Both the initial concentrations and air flow rate were varied to study the suitable conditions of PM removal. After that, the efficiency of SF fiber for PM removal was measured by the Side Pak Personal Aerosol Monitor (AM 510).

Phase 3: The silk fibroin fiber characterization.

Morphological structure of the SF fiber was examined using a scanning electro microscope (SEM). The physical properties of the SF fiber including specific surface area, specific pore volume, and pore size were analyzed by the Barrett Joyner Halenda (BJH) method. The mechanical properties of the SF fiber were studied with tensile strength.

Phase 4: The efficient comparison of particle removal of silk fibroin fiber and commercial fiber.

The SF fiber and commercial fiber were used as a filter for filtration during 8-hour. Both the initial concentrations and air flow rate were varied to study the suitable conditions of PM removal. The efficiency of the SF fiber and the commercial fiber for PM removal was measured by the Side Pak Personal Aerosol Monitor (AM 510). After that, the efficiencies of particle removal of the SF fiber and the commercial fiber were compared.

CHAPTER II

BACKGROUND AND LITERATURE REVIEWS

2.1 Silkworm silk

Silk is a natural biopolymer produced by silkworms during the formation of their cocoon. There are two main types of the silkworms, mulberry silk or *Bombyx mori* which is also called cultivated silk, and wild silk such as *Samia Cynthia ricini* or *A.pernyi*. Cultivated silk are fine, almost white and soft filaments with luster. The world silk production consists of nearly 80-85% of cultivated silks. While wild silks are coarser, more irregular and brownish in appearance, they are never as white as the cultivated silk filament. Thai silk is one of the mulberry silkworm (*Bombyx mori)* silks but it differs somewhat in the appearance. It is yellower in colour, the filaments are coarser, and it has more silk gum. The process of remove sericin is known as degumminig. The silk fiber can be divided from silkworm into 2 types that are (Moy, R. L., *et al*., 1991):

1. **Mulberry silk** (*Bombyx mori*) is produced by cultivated silkworm. The cultivated silkworm is fed with mulberry leaves.
2. **Wild silk** is produced by wild silkworm .This type often referred as **Tussah silk** .The wild silkworm is fed with oak leaves.

The wild silkworm is hard to culture and the silk fibers obtained from wild silkworm are coarser, more irregular, and brownish in appearances. While the silk fibers obtained form cultivated silkworm are fine, almost white (when degummed), and soft fiber with lusture. Moreover, wild silkworm' fiber has more silk gum (e.g. up to 38%) than *Bombyx mori (B. mori)* silkworm' fiber (20-25%). From these characteristic, silk fiber produced by *B. mori* silkworm is well known and has been studied extensively in biomaterial application.

Silk consists of two natural macromolecular proteins, fibroin and sericin. Both of their molecular weights range from about 10,000 to over 300,000 Da. Fibroin is continuous protein with crystalline structure and is water-insoluble. It can be regenerated in several forms such as gel, powder, fiber, or membrane.

The domesticated silkworm (*B. mori*) silk fibroin fibers are about 10–25 mm in diameter and consist of two proteins: a light chain (_26 kDa) and heavy chain (_390 kDa) which are present in a 1:1 ratio and linked by a single disulfide bond. These proteins are coated with a family of hydrophilic proteins called sericins (20–310 kDa) (Zhou, C. Z., *et al*., 2000). The disulfide linkage between the Cys-c20 (20th residue from the carboxyl terminus) of the heavy chain and Cys-172 of the light chain holds the fibroin together and a 25 kDa glycoprotein, named P25, is noncovalently linked to these proteins (Tanaka, K., *et al*., 1999).

Silk fibroin is purified from sericins by boiling silk cocoons in an alkaline solution (Fig. 2.1). Twenty-five to thirty percent of the silk cocoon mass is sericin, which is removed during the de-gumming process.

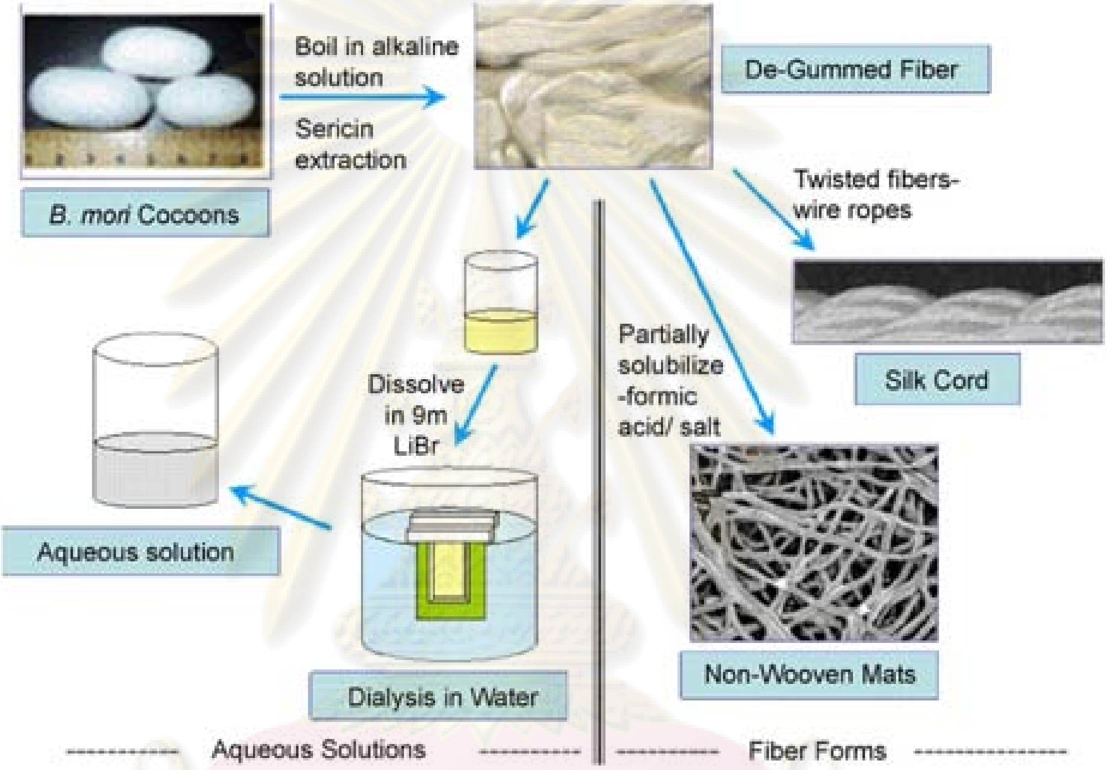


Fig. 2.1 Silk fibroin is purified from sericins via boiling in an alkaline solution. The de-gummed or purified silk fibers can be processed into silk cords by twisting; non-woven silk mats by partial solubilization; or dissolved in lithium bromide, dialyzed and formed into aqueous silk fibroin solution for preparation of other material morphologies.

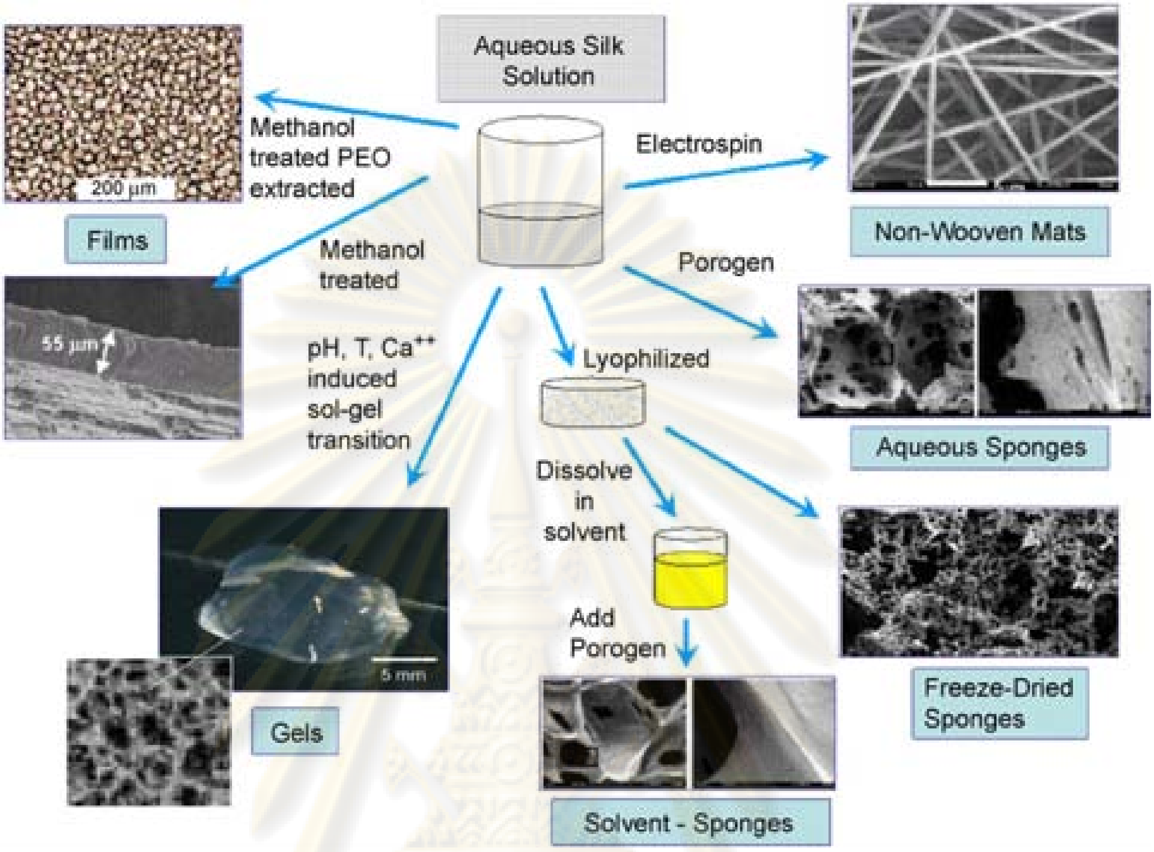


Fig. 2.2 Processing of silk morphologies from aqueous silk fibroin solution into non-woven silk fibers; aqueous- and solvent-based porous sponges; hydrogels and films.

Fibroin is one of the candidate materials for biomedical application because of its various characteristic such as good biocompatibility, good oxygen and water vapor permeability, and minimal inflammatory reaction. Additionally, fibroin has been used in cosmetic, medical material for human health, and food additive.

Serisin, or silk gum is a globular protein, an amorphous structure, water soluble glue and it also has some impurities such as waxes, fats, and pigments. Serisin constitutes 25-30% of silk protein and it envelops the fibroin fiber with continuing sticky layer and that provide the cohesion of the cocoon by gluing silk threads together. Removal of sericin from the silk fibroin is achieved by the process call degumming. When subjected to the degumming process, physically, chemically, or enzymologically, the sericin protein is degraded into polypeptide. The sericin peptide has excellent moisture absorption and releases a lot of biological activities such as antioxidant, anti-cancer activities and can be applied to degradable biomaterials. Furethermore, sericin is also used as a coating material for natural and artificial fibers which can prevent abrasive skin injuries (Moy, R.L., *et al*., 1991).

2.1.1 *Bombyx mori* silk fibroin structure

The amino acid composition of silk fibroin from *B. mori* consists primarily of glycine (Gly) (43%), alanine (Ala) (30%) and serine (Ser) (12%) (Kaplan, D. L., *et al*., 1998). The heavy chain consists of 12 domains that form the crystalline regions in silk fibers, which are interspersed with primary sequence that is non-repetitive and thus forms fewer organized domains in the fibers. The crystalline domains in the fibers consist of Gly-X repeats, with X being Ala, Ser, Threonine (Thr) and Valine (Val). The crystalline forming domains consist of an average of 381 residues (596 in size in the seventh domain to 36 in the 12th domain). Each domain consists of sub-domain hexapeptides including: GAGAGS, GAGAGY, GAGAGA or GAGYGA where G is glycine, A is alanine, S is serine and Y is tyrosine. These subdomains end with tetrapeptides such as GAAS or GAGS. The less crystalline forming regions of the fibroin heavy chain, also known as linkers, are between 42 and 44 amino acid residues in length. All the linkers have an identical 25 amino acid residue (non-repetitive sequence), which is composed of charged amino acids not found in the crystalline regions (Zhou, C. Z., *et al.,* 2001). The primary sequence results in a hydrophobic protein with a natural coblock polymer design. Efficient secretion of fibroin is believed to be due in part to the formation of a disulfide bond between the heavy and light fibroin chains. A naked pupa mutation in *B. mori* has been mapped to the same locus as of the light chain on the 14th chromosome. The resulting fibroin light chain does not have a disulfide bond with the fibroin heavy chain and the cocoon has less than 0.3% fibroin protein content.

Silk fibroin (SF) is a core structural protein and is coated by sericin (silk gum), a family of glue- like proteins that hold the fibroin core fibers together. The sericin is a minor component of fiber (i.e. 25% of the weight of raw silk) and it also has some purities such as waxes, fat, and pigments. Silk fibroin is a fibrous protein unlike sericin which is a globular protein. The elemental compositions in SF are listed in the Table 2.1

Table 2.1 The composition of elements in silk fibroin
(Vollrath, F. and Knight, D. P., 2001).

Element	Percentages of element
Carbon	48-49
Hydrogen	6.40-6.51
Nitrogen	17.35-18.89
Oxygen	26.00-27.90
Sulphur	Slightly

The Silk fibroin is a semi-crystalline protein polymer that consists of beta-sheet crystals and non-crystalline amorphous regions Gosline, *et al*., 1987 (Fig. 2.3). Silk fibroin is a linear polypeptide whose chemical composition comprised of few types of amino acid of alternating of Glycine (Gly) residue with two thirds Alanine (Ala) and one third Serine (Ser). Fibroin has a highly repetitive primary structure that contains of the motif -Gly-Ala-Gly-Ala-Gly-Ser- along its sequence. It is composed of the alpha form consisting of crank shaft, pleated beta-sheet formation (Fibroin I) and the beta formation consisting of anti-parallel pleated beta-sheet formation (Fibroin II) (Magoshi *et al*., 1994). The polypeptide chains (Fig. 2.3) always form anti- parallel β-sheet because this structure has hydrogen bonds (H-bond) between peptide groups on adjacent beta strands and these H-bonds can stabilize structure.

Sericin, on the other hand, is a mixture of proteins, which contains Ser, Thr and Tyr. It is amorphous and soluble in water.

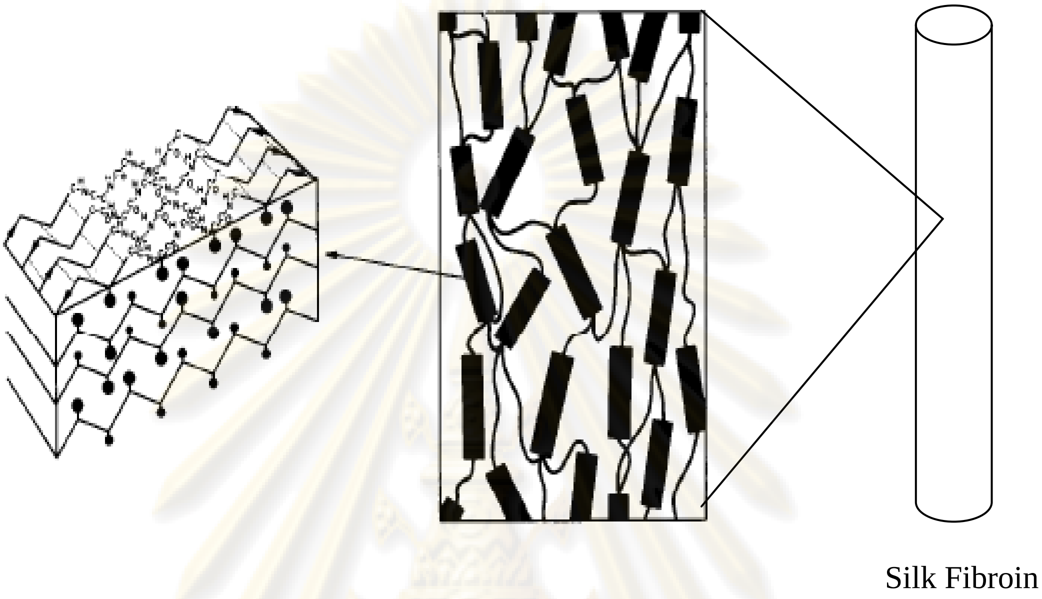


Fig. 2.3 Model of microstructure found in silk fibroin. Black rectangles represent beta-sheet crystallites and lines represent amorphous regions (Gosline, *et al*., 1987).

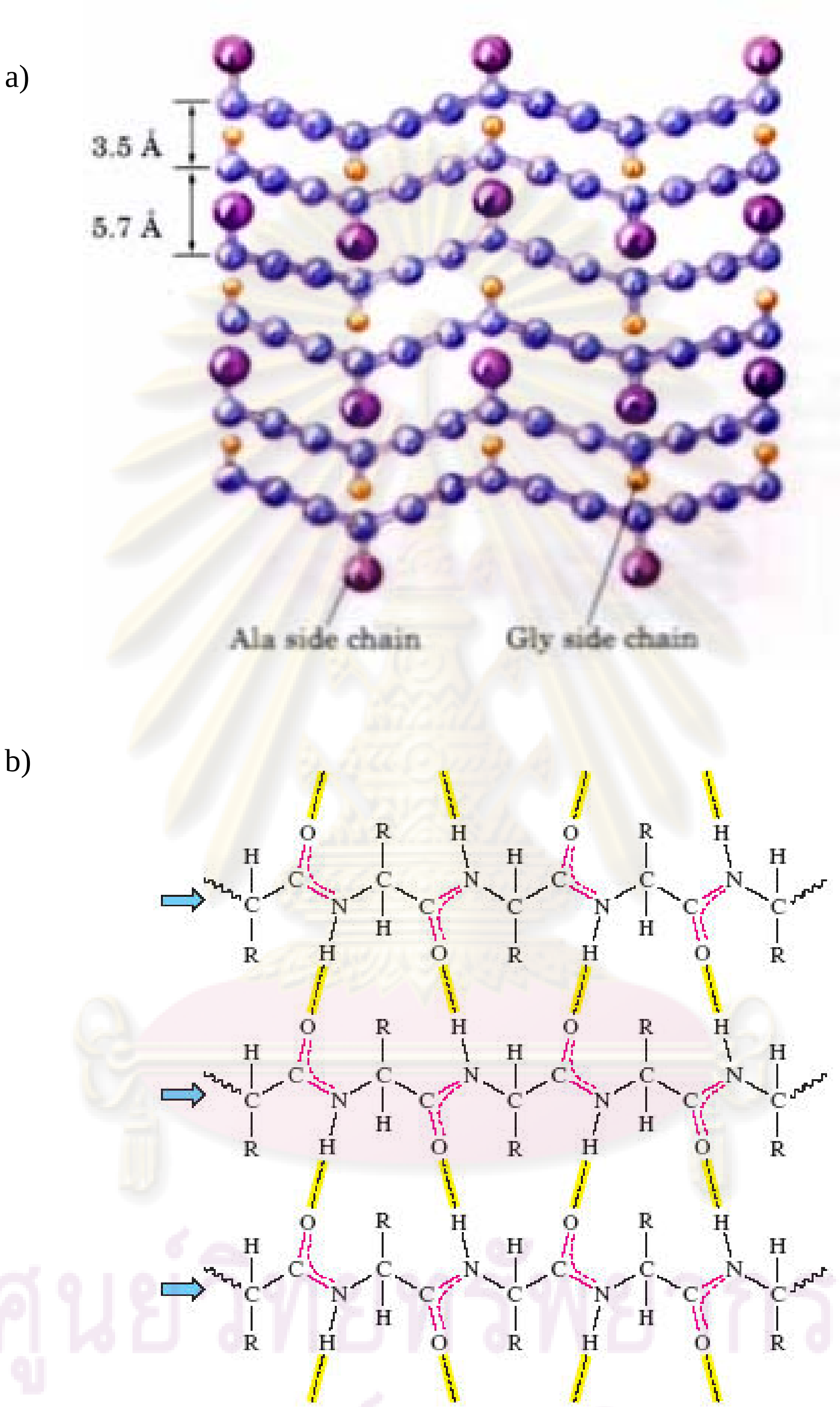


Fig. 2.4 a) and b) The polypeptide chain of silk fibroin consists of layers antiparallel β-sheets rich in Ala and Gly residues.

Silk fibers after degumming are approximately 900-1,700 meters long and the diameter ranges from 9 to 11 microns. Silk fibers are extremely strong. A filament of silk is stronger than steel with an equal diameter, but the strength of the fiber is reduced greatly when it is wet (about 80-85% of the dry strength). If silk fiber is heated at 140° C , it will remain unaffected for a long period of time but it is decomposed very quickly at the temperature of 175 ° C or higher. As show in Fig. 2.4, because the silk fibers have extensive hydrogen bonding, the abundant hydrophobic nature of their proteins, and the significant crystalline structure of the polypeptide chains in silk fibroin, so silk fibers are insoluble in most solvents, including water, dilute acid and alkali.

Table 2.2 The composition of amino acid in silk fiber (%) (Zhou, C. Z., *et al.*, 2001).

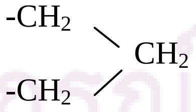
Type	Side group(R-group)	Amino acid	Proportion
Inert	$-H$ $-CH_3$ $-CH(CH_3)_2$ $-CH_2CH(CH_3)_2$ $-CH(CH_3)CH_2CH_3$ $-CH_2C_6H_5$	Glycine Alanine Valine Leucine Isoleucine Phenylalanine	46.39 44.55 0.50 0.05 0.08 0.02
Acidic	$-CH_2COOH$ $-CH_2CH_2COOH$	Aspartate Glutamate	0.17 1.03
Basic	$-CH_2CH_2CH_2CH_2NH_2$ $-(CH_2)_3NHC(NH)NH_2$	Lysine Arginine	0.07 0.17
Hydroxyl	$-CH_2OH$ $-CH(OH)CH_3$ $-CH_2C_6H_4OH$	Serine Threonine Tyrosine	7.17 0.15 0.14
Ring	 $-CH_2$ CH_2 $-CH_2$	Proline	0.02
Sulfur	$-CH_2-S-S-CH_2-$ $-CH2CH_2-S-CH_3$	Cysteine Methionine	0.02 0.04

Table 2.2 lists the composition of amino acid in silk fibers. There are different proportions of amino acid residues in fibroin and sericin. Fibroin has higher proportions of alanine, glycine, and serine than leading to antiparallel β - pleated sheet formation. The crystalline regions of silk fibers are composed mainly of repeating unit of amino acid in silk fibroin chains. *Bombyx mori* and *A.pernyi* silk fibroin are composed mainly of -(alanine-alanine)$_n$ -sequences, while -(glycine-alanine) $_n$ -repetitions are characteristic to *Bombyx mori* silk fibroin. A small amount of cysteine and methioinine residues give a very small amount of sulfur in the fiber (Moy, R.L., *et al*., 1991).

A number of silk polymorphs have been reported, including the glandular state prior to crystallization (silk I), the spun silk state which consists of the β-sheet secondary structure (silk II), and an air/water assembled interfacial silk (silk III, with a helical structure). The silk I structure is the water-soluble state and upon exposure to heat or physical spinning easily converts to a silk II structure. The silk I structure is observed in vitro in aqueous conditions and converts to a β-sheet structure when exposed to methanol or potassium chloride. The β-sheet structures are asymmetrical with one side occupied with hydrogen side chains from glycine and the other occupied with the methyl side chains from the alanines that populate the hydrophobic domains. The β-sheets are arranged so that the methyl groups and hydrogen groups of opposing sheets interact to form the intersheet stacking in the crystals. Strong hydrogen bonds and van der Waals forces generate a structure that is thermodynamically stable. The inter- and intra-chain hydrogen bonds form between amino acids perpendicular to the axis of the chains and the fiber. The silk II structure excludes water and is insoluble in several solvents including mild acid and alkaline conditions, and several chaotropes (Kaplan, D. L., *et al*., 1998).

The silk II structure is identified by the ^{13}C chemical shifts that are indicative of anti- parallel β-sheet, while the silk I structure gives the chemical shifts that are related with a loose helix. The two structures can undergo a conformational transition form silk depending on any factors such as solvent, temperature, or shear and tensile stresses (Tanaka, K., *et al.*, 1999). The region of anti- parallel β-sheet is a crystal region which results in the stability and mechanical features of silk fibroin.

2.1.2 *Bombyx mori* silk sericin

The sericin coating constitutes 25–30% of the weight of *B. mori*'s silk fibre, and helps in the formation of silk cocoon by gluing the fibres together. It is made of sericins, gum-like proteins that vary in their molecular weight between 10 and 300 kDa, and are rich in the amino acid serine. It is also thought to contain carotenoids, which are responsible for cocoon pigmentation. Sericins are known to have several extraordinary properties: they resist oxidation, are antibacterial, UV resistant, and can absorb and release moisture easily (Rammensee S., *et al*., 2006). These properties are valuable in the protection of silk from microbial degradation, animal digestion, and other damaging processes. Recent studies show some surprising properties of sericin; dietary sericin has been suggested to suppress the development of colon tumours by reducing cell proliferation, and creating oxidative stress and nitric acid production.

It has also been found, under certain conditions, to induce bone-like apatite deposition (Solheim, E., *et al.*, 2000). However, sericin is still considered an obstacle for *B. mori* silk biocompatibility, despite the coating being soluble in hot alkaline water and therefore removable. As discussed later in this review, insufficient sericin removal is still an issue in many biomedical applications.

2.2 Structure of silk threads

It is now clear that there is a strong connection between the structure of silk fibres and their physical (and mechanical) properties. Structural organisation from protein sequence, through protein folding to the assembly of the fibrils appears to play a role in the toughness and elasticity of silk fibres (Zhou, C. Z., *et al*., 2001). Relating structural features and patterns to physical properties is valuable as it could contribute to the ability to control the properties of future man-made silk analogous (for example, an ability to control mechanical properties by introducing a certain structural features to the thread during spinning could be beneficial). However, an understanding the structure of silk threads is still a challenge. Below is a review of the main structural features of silkworm and spider silks, starting at the overall thread organization and going down to the protein makeup.

Most natural silk threads known to date are thought to consist of an inner silk core of polymer protein, a protein skin, and some type of coating. The core exhibits nanofibrils, with some assembled into bundles called microfibrils. Generally, the coating functions as glue, but there is some evidence that it may also act as a fungicidal or bactericidal agent. It may also have a role during the extrusion process. Micro-morphological studies show that the substructure of spider silks is very similar to that of mulberry silkworm silks. *B. mori* silk fiber has been shown to be composed of two protein-monofilaments (named brins) embedded in a gluelike sericin coating. A similar structure has been observed in other silkworms silk. The brins are fibroin filaments made up of bundles of nanofibrils, approx 5 nm in diameter, with a bundle diameter of around 100 nm. The nanofibrils are oriented parallel to the axis of the fibre, and are thought to interact strongly with each other (Meinel, L., *et al.,* 2004). A schematic representation of the structure of *B. mori* thread is shown in Fig. 2.5

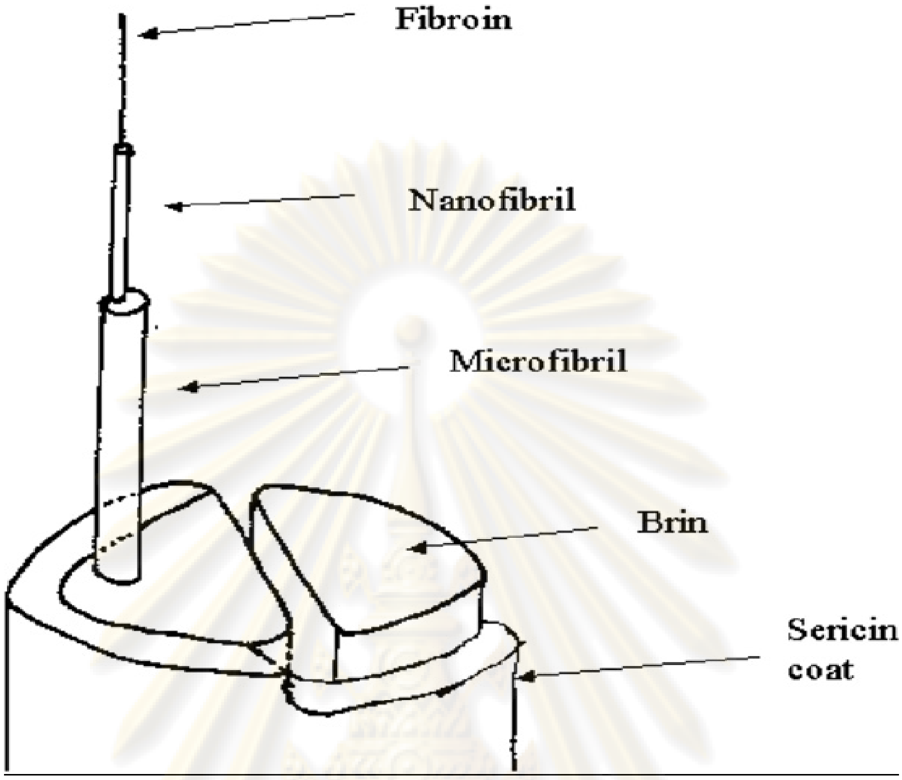


Fig. 2.5 The structure of a raw silk filament (Meinel, L., *et al.*, 2004).

Fig. 2.5 present the structure of raw silk filament, which contains microfibrils that are packed together to form the fibril bundle. The several fibril bundles produce a single strand of fibroin. Sericin envelops two strand of fibroin together to form a raw silk filament. Both contain elongated tubular cavities or vacuoles called canaliculi. The role of these canaliculi may be to facilitate controlled crack formation in the fibres when it is stretched or loaded. Although thread diameter varies across silk types and species, the mean width of nanofibrils appears to be independent of the fibre size, ranging 90–170 nm (Putthanarat, S., *et al*., 2000).

A comparison of mechanical properties (Table 2.3) suggests that *Bombyx mori* silk provide a remarkable combination of strength and toughness. The distinguishing features of the silk fibroin filaments following extraction of sericin are the very high strength in combination with excellent elasticity in comparison with these other biomaterials. In additionally, these fibers display resistance to failure in compression that distinguishes them from other high performance fiber such as Kevlar.

Table 2.3 Comparison of mechanical properties of common silks (silkworm and spider dragline) to several types of biomaterial fibers and tissues commonly used today.

Material	Tensile Strength (MPa)	Modulus(GPa)	% Strain at break
B. mori silk (w/ sericin)[a]	500	5–12	19
B. mori silk (w/o sericin)[b]	610–690	15–17	4–16
B. mori silk[c]	740	10	20
Spider silk[d]	875–972	11–13	17–18
Collagene	0.9–7.4	0.0018–0.046	24–68
Collagen X-linked[f]	47–72	0.4–0.8	12–16
PLA[g]	28–50	1.2–3.0	2–6
Tendon (comprised of mainly collagen)	150	1.5	12
Bone	160	20	3
Kevlar (49 fiber)	3600	130	2.7
Synthetic Rubber	50	0.001	850

[a] *Bombyx mori* silkworm silk—determined from bave (multithread fibers naturally produced from the silk worm coated in sericin).

[b] *Bombyx mori* silkworm silk—determined from single brins (individual fibroin filaments following extraction of sericin).

[c] *Bombyx mori* silkworm silk—average calculated from data in Ref. Cunniff , P. M., *et al.*, 1994

[d] Nephila clavipes silk produced naturally and through controlled silking.

[e] Rat-tail collagen Type I extruded fibers tested after stretching from 0% to 50%.

[f] Rat-tail collagen dehydrothermally cross-linked and tested after stretching from 0% to 50%.

[g] Polylactic acid with molecular weights ranging from 50,000 to 300,000.

Because of the impressive mechanical properties including biological properties, biocompatibility and biodegradability, the SF has been interested in various not only textile fields but also in reinforcing composites, food additive, cosmetic, and biomedical fields. Particularly, SF has been researched extensively in the biomedical fields. The applications of SF in the biomedical fields are controlled drug-delivery carrying, cell culture substrate, sutures, tissue engineering matrix, and wound dressing. The SF can be prepared as regenerated SF in various forms such as gel, powders, membranes, or fibers depending on desired application.

For Filter application of the electrospun material is considered as a special interest for industrialization. Recently, water permeable nanofibrous membrane is discussed widely and developed a fibrous membrane via electrospun nanofibrous web for liquid separation and electrospun nanofibrous applicability in particulate removal. In 2006, Gopal, *et al*., investigated a permeability of the electrospun nanofibrous membrane with varying parameters of the membrane structure such as fiber diameter, porosity and thickness. It was reported that an electrospun Polyvinylidene fluoride nanofibers (PVDF) nanofibrous membrane could be used for separation of microscale particles and an application to an affinity membrane was also reported for electrospun cellulose nanofiber having large surface area to volume ratio. The viability of developing a fibrous membrane via electrospun nanofibrous web for liquid separation and demonstrates its applicability in particulate removal. Polyvinylidene fluoride nanofibers were electrospun into membranes and characterized to relate its structural properties to membrane separation properties and performance. Characterization of these electrospun membranes revealed that they have similar properties to that of conventional microfiltration membranes. The electrospun membranes were used to separate 1, 5 and 10 μm polystyrene particles. The electrospun membranes were successful in rejecting more than 90% of the micro-particles from solution. This work opens up the avenue of exploring the use of nanofibers for more mainstream application in the separation technology as a potential membrane for pre-treatment of water prior to reverse osmosis or as pre-filters to minimize fouling and contamination prior to ultra- or nano-filtration. (Gopal, *et al*., 2006)

Recently In 2007, Chang, S. K., *et al*., study, silk fibroin (SF) and wool keratose/silk fibroin (WK/SF) blend nanofibrous membranes were prepared by electrospinning and their performances were evaluated as a heavy metal ion adsorbent. The electrospun nanofibrous membranes were comprised of randomly oriented ultra-fine fibers of 200–400 nm diameters. As a result of pressure–flux test, the membranes exhibited similar flux to ordinary microfiltration membrane. Metal ion adsorption test was performed with Cu2+ as a model heavy metal ion in a stock solution. Due to large surface area and high porosity of electrospun nanofibrous structure, the nanofibrous membranes exhibited high metal ion capacities compared with common fibrous filters (wool sliver and filter paper). Especially, the WK/SF blend nanofibrous membrane had an exceptional performance for the adsorption of metal ions. Furthermore, its adsorption capacity has been maintained after several recycling process (desorption and re-adsorption) which is very advantageous as an affinity membrane. The electrospun WK/SF nanofibrous membrane is very suitable for removing and recovering heavy metal ions in water. (Chang, S. K., *et al.*, 2007)

2.3 Indoor air environment

Indoor air quality has received immense attention in the early 1990s. This is because studies (Jones, 1999) showed that the level of pollutants in indoor environment is actually higher than in outdoor environment. In addition, people generally spend more than 80 % of their time in indoors, which contributes a higher risk from inhalation of pollutants than outdoors (Robinson and Nelson, 1995). In 1995, USEPA identified indoor air pollution is one of the top environmental risk (USEPA, 1995).

Indoor air environments must meet the requirement of thermal comfort and IAQ. Thermal comfort is affected by many factors, which mainly include air temperature, air humidity, air velocity, mean radiant temperature, human clothing, and activity levels. The wide use of air conditioning helps to improve thermal comfort, but health problems associated with poor IAQ appear more frequently (e.g., SBS) (Niu, 2004). Many experts believe that IAQ may be the most important and relatively overlooked environmental issue of our time (Gao, 2002). It is indoor pollutants that lead to poor IAQ. Indoor air pollutants consist of both particle pollutants and gaseous pollutants. Particle pollution, also called particulate matter or PM, is a mixture of microscopic solids and liquid droplets suspended in air. This pollution, also known as particulate matter, is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, soil or dust particles, and allergens (such as fragments of pollen or mold spores).

2.3.1 Particle pollutants

Particle pollution (also called particulate matter or PM) is the term for a mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small, they can only be detected using an electron microscope. These particles come in many sizes and shapes and can be made up of hundreds of different chemicals. Some particles, known as *primary particles* are emitted directly from a source, such as construction sites, unpaved roads, fields, smokestacks or fires. Others form in complicated reactions in the atmosphere of chemicals such as sulfur dioxides and nitrogen oxides that are emitted from power plants, industries and automobiles. These particles, known as *secondary particles*, make up most of the fine particle pollution in the country.

The size of particles is directly linked to their potential for causing health problems. Small particles less than 10 micrometers in diameter pose the greatest problems, because they can get deep into your lungs, and some may even get into your bloodstream. Exposure to such particles can affect both your lungs and your heart. Larger particles are of less concern, although they can irritate your eyes, nose, and throat. The revised 2006 standards address two categories of particle pollution:

- "Inhalable coarse particles," such as those found near roadways and dusty industries, are larger than 2.5 micrometers and smaller than 10 micrometers in diameter.

- "Fine particles," such as those found in smoke and haze, are 2.5 micrometers in diameter and smaller. These particles can be directly emitted from sources such as forest fires, or they can form when gases emitted from power plants, industries and automobiles react in the air.

Sawant, *et al.*, 2004 and Cao, *et al.*, 2002 investigated the chemical characteristics of $PM_{2.5}$. The main composition of $PM_{2.5}$ and mass percentage inside the residences are organic carbon (40–60%), nitrate (13–14%), trace elements (11–12%), ammonium (8%), elemental carbon (6%), and sulfate (4%). The main composition of $PM_{2.5}$ and mass percentage at the schoolroom sites are organic carbon (26–50%), nitrate (20%), trace elements (22%), elemental carbon (6–7%), and sulfate (6–7%). From the results above, it can be found that organic carbon is the largest contributor to $PM_{2.5}$, and has largest impact on the characteristics of $PM_{2.5}$. $PM_{2.5}$ containing much organic carbon not only contribute to the propagation of bacteria, but help bacterial spread. $PM_{2.5}$ endanger occupants' health directly or indirectly. Furthermore, the dust accumulating on hot surfaces (e.g., heaters and light fixtures) is likely to emit chemicals when heated. (Sawant, *et al*., 2004 and Cao, *et al*., 2002)

Particle pollutants endanger human body through three approaches, namely respiration canal, skin, and alimentary canal. It is the most dangerous approach that particle pollutants enter human body through respiration canal (Kavouras and Stephanou, 2002). The harm degree of particle pollutants to human body is related to the chemical characteristic, diameter magnitude, and quantity. The chemical characteristic of particle pollutants is the main factor because the chemical characteristic determines the degree and speed of biochemistry processes which particle pollutants participate in and disturb in human body. Most of the particle pollutants in air are quite small. They have difficulty in settling and being captured. Conversely, it is easy for them to enter respiration canal deeply together with inhaled air. Moreover, the surface of particle pollutants can adsorb harmful gases, liquid and microbe, which increases the harm to human body. The exposure can lead to a variety of health effects. For example, numerous studies link particle levels to increased hospital admissions and emergency room visits and even to death from heart or lung diseases. Both long- and short-term particle exposures have been linked to health problems.

Long-term exposures, such as those experienced by people living for many years in areas with high particle levels, have been associated with problems such as reduced lung function and the development of chronic bronchitis and even premature death.

Short-term exposures to particles (hours or days) can aggravate lung disease, causing asthma attacks and acute bronchitis, and may also increase susceptibility to respiratory infections. In people with heart disease, short-term exposures have been linked to heart attacks and arrhythmias. Healthy children and adults have not been reported to suffer serious effects from short-term exposures, although they may experience temporary minor irritation when particle levels are elevated.

When breathed in, these particles can reach the deepest regions of the lungs. Exposure to particle pollution is linked to a variety of significant health problems, ranging from aggravated asthma to premature death in people with heart and lung disease. Particle pollution, especially fine particles contains microscopic solids or liquid droplets that are so small that they can get deep into the lungs and cause serious health problems. Numerous scientific studies have linked particle pollution exposure to a variety of problems, including:

- increased respiratory symptoms such as irritation of the airways coughing or difficulty breathing
- decreased lung function
- aggravated asthma
- development of chronic bronchitis
- irregular heartbeat
- nonfatal heart attacks
- premature death in people with heart or lung disease

One of the major sources of indoor air particles is rice mills paeticularly from a rice milling process (Sumanno, S., 2007). In Thailand have more industrializations of rice mill, especially in Ubonratchatani province rice mill has therefore caught the interest not only of scientists, but of the general public as well. The total invest industrialization in Ubonratchatani province are 3,951 factories, total investment 12,104,654 millions baht and employment 15,502 persons .The most investitive industrialization is rice mill , these have 3,951 factories and also equally 78.23 % of total factory. The small rice mill that it has power production below 18 bullock cart per day are 259 small rice mills. (www.thai ricemillers.com). Good air quality in working places benefits workers in their working ability, helps keep workers and staff productive, and also is beneficial to their health Indoor air quality in rice mill is affected by milling process activities, as well as particularly frying rice mill is among the most important sources of particles indoors air.

2.3.2 Pollution and properties of rice bran from rice mill process

Rice bran is generated during the rice milling process. From a nutritional point of view, it is the most valuable byproduct. Rice bran consists of the outer layers (pericarp, aleurone, germ, and part of the endosperm) of the rice kernel that are removed during whitening and polishing of husked rice. When paddy is hand-pounded or milled in a one-pass Engleberg steel huller, rice bran is not produced separately but mixed with rice hulls. (www.fao.org.com)

- Out of 100 kg paddy rice, 5 to 8 kg of bran can be typically produced.
- Moisture content of rice bran is in the 10 to 15 % range, on wet weight basis
- Rice bran is a mixture of substances, including protein, fat, ash, and crude fiber. In many cases, bran contains tiny fractions of rice hull, which increases the ash content of bran.
- Bran composition is largely dependent on the milling process. In modern rice mills several different kinds of bran are produced: coarse bran (from the first whitening step), fine bran (from second whitening step) and polish (from the polishing step). Polish consists of part of the endosperm and is often referred to as meal.
- Rice bran has a high nutritive value. Besides proteins, rice bran is an excellent source of vitamins B and E. Bran also contains small amounts of anti-oxydants, which are considered to low cholesterol in humans.
- Rice bran contains 10-23 % bran oil. The oily nature makes bran an excellent binder for animal feeds. Bran oil, once stabilized and extracted, is a high quality vegetable oil for cooking or eating.
- Rice Bran has a wide particle size distribution. The particle size distribution is strongly affected by the milling conditions.

2.3.3 Particle health effects

The effects of inhaling particulate matter have been widely studied in humans and animals and include asthma, lung cancer, cardiovascular issues, and premature death. The size of the particle is a main determinant of where in the respiratory tract the particle will come to rest when inhaled. Larger particles are generally filtered in the nose and throat and do not cause problems, but particulate matter smaller than about 10 micrometres, referred to as PM_{10}, can settle in the bronchi and lungs and cause health problems. The 10 micrometer size does not represent a strict boundary between respirable and non-respirable particles, but has been agreed upon for monitoring of airborne particulate matter by most regulatory agencies. Similarly, particles smaller than 2.5 micrometres, $PM_{2.5}$, tend to penetrate into the gas-exchange regions of the lung, and very small particles (< 100 nanometers) may pass through the lungs to affect other organs. In particular, a study published in the *Journal of the American Medical Association* indicates that $PM_{2.5}$ leads to high plaque deposits in arteries, causing vascular indicates that $PM_{2.5}$ leads to high plaque deposits in arteries, causing vascular inflammation and atherosclerosis a hardening of the arteries that reduces elasticity, which can lead to heart attacks and other cardiovascular problems.

Researchers suggest that even short-term exposure at elevated concentrations could significantly contribute to heart disease. The smallest particles, less than 100 nanometers (nanoparticles), may be even more damaging to the cardiovascular system. There is evidence that particle smaller than 100 nanometres can pass through cell membranes and migrate into other organs, including the brain. It has been suggested that particulate matter can cause similar brain damage as that found in Alzheimer patients. Particles emitted from modern diesel engines (commonly referred to as Diesel Particulate Matter or DPM) are typically in the size range of 100 nanometres (*0.1 micrometres*). In addition, these soot particles also carry carcinogenic components like benzopyrenes adsorbed on their surface. It is becoming increasingly clear that the legislative limits for engines, which are in terms of emitted mass, are not a proper measure of the health hazard. One particle of 10 µm diameters has approximately the same mass as 1 million particles of 100 nm diameters, but it is clearly much less hazardous, as it probably never enters the human body - and if it does, it is quickly removed. Proposals for new regulations exist in some countries, with suggestions to limit the particle surface area or the particle number. The large number of deaths and other health problems associated with particulate pollution was first demonstrated in the early 1970s and has been reproduced many times since. PM pollution is estimated to cause 22,000-52,000 deaths per year in the United States (from 2000) and 200,000 deaths per year in Europe.

The health of lungs and entire respiratory system is affected by the quality of the air breathe. Aside from the oxygen need, air contains other substances such as pollutants, which can be harmful. The lungs are built to bring large quantities of air (on average, 400 million liters in a lifetime) into the body, to deliver oxygen. Air pollutants can hinder the lungs from being able to collect and deliver oxygen. But more importantly, they can cause long-term tissue damage or exacerbate existing health concerns such as:

- Asthma
- Emphysema and chronic bronchitis known together as chronic obstructive pulmonary disease (COPD)

The young, old and smokers are generally the most at risk from poor air quality.

1) Asthma

Asthma can be aggravated by exposure to air pollution. Asthma causes the lung's bronchial tubes (airways) to become inflamed and swollen, blocking the flow of air and causing symptoms like wheezing, coughing, chest tightness and shortness of breath. Asthma imposes a heavy burden on the nation's health care expenditures and reduces the quality of life for individuals with asthma and their families.

The exact cause of asthma is unknown, but it appears to be the result of a complex interaction of three factors:

1. Predisposing factors, such as a topy - a tendency to have an allergic reaction to foreign substances.
2. Causal factors, which may sensitize the airways, such as cat and other animal dander, dust mites, cockroaches, or workplace contaminants.
3. Contributing factors, which may include maternal cigarette smoking during pregnancy or exposure to cigarette smoke as a child, respiratory infections, and indoor and outdoor air quality.

2) Chronic obstructive pulmonary disease

Chronic obstructive pulmonary disease (COPD) causes shortness of breath, coughs and sputum production. COPD can also be referred to as chronic bronchitis and emphysema, which are both linked to and most commonly caused by cigarette smoking. As the disease progresses, people with COPD experience a reduced quality of life and limited activity levels caused by severe shortness of breath.

The number of individuals with COPD may increase in the near future. The incidence of COPD should decrease in the long term. While cigarette smoking is the main cause of COPD, outdoor air pollution may contribute to the development or the aggravation of COPD.

3) Cardiovascular diseases

The health of heart and entire cardiovascular system can be affected by the quality of the air breathe. Aside from the oxygen need, air contains other substances such as pollutants, which can be harmful.

Breathing in these pollutants can hurt to heart and other organs because pollution is absorbed into bloodstream as breathe. Once the chemicals in pollutants are in bloodstream they can travel throughout body and start a chemical chain reaction. This can affect to blood vessels and ultimately heart.

2.3.4 National ambient air quality standards (NAAQS) for six principal pollutants

The EPA Office of Air Quality Planning and Standards (OAQPS) has set National Ambient Air Quality Standards for six principal pollutants, which are called "criteria" pollutants. They are listed below. Units of measure for the standards are parts per million (ppm) by volume, milligrams per cubic meter of air (mg/m^3), and micrograms per cubic meter of air (µg/m^3).

Table 2.4 National ambient air quality standards for six principal pollutants

	Primary Standards		**Secondary Standards**	
Pollutant	**Level**	**Averaging Time**	**Level**	**Averaging Time**
Carbon Monoxide	9 ppm (10 mg/m^3)	8-hour(1)	None	
	35 ppm (40 mg/m^3)	1-hour(1)		
Lead	1.5 µg/m^3	Quarterly Average	Same as Primary	
Nitrogen Dioxide	0.053 ppm (100 µg/m^3)	Annual (Arithmetic Mean)	Same as Primary	
Particulate Matter (PM_{10})	150 µg/m^3	24-hour(2)	Same as Primary	
Particulate Matter ($PM_{2.5}$)	15.0 µg/m^3	Annual(3) (Arithmetic Mean)	Same as Primary	
	35 µg/m^3	24-hour(4)	Same as Primary	
Ozone	0.075 ppm (2008 std)	8-hour(5)	Same as Primary	
	0.08 ppm (1997 std)	8-hour(6)	Same as Primary	
	0.12 ppm	1-hour(7) (Applies only in limited areas)	Same as Primary	
Sulfur Dioxide	0.03 ppm	Annual (Arithmetic Mean)	0.5 ppm (1300 µg/m^3)	3-hour(1)
	0.14 ppm	24-hour(1)		

(1) Not to be exceeded more than once per year.

(2) Not to be exceeded more than once per year on average over 3 years.

(3) To attain this standard, the 3-year average of the weighted annual mean $PM_{2.5}$ concentrations from single or multiple community-oriented monitors must not exceed 15.0 µg/m^3.

(4) To attain this standard, the 3-year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 35 µg/m^3.

(5) To attain this standard, the 3-year average of the fourth-highest daily maximum 8-hour

average ozone concentrations measured at each monitor within an area over each year must not exceed
0.075ppm.

[6] (a) To attain this standard, the 3-year average of the fourth-highest daily maximum 8-hour average ozone concentrations measured at each monitor within an area over each year must not exceed 0.08 ppm. (b) The 1997 standard and the implementation rules for that standard will remain in place for implementation purposes as EPA undertakes rulemaking to address the transition from the 1997 ozone standard to the 2008 ozone standard

[7] (a) The standard is attained when the expected number of days per calendar year with maximum hourly average concentrations above 0.12 ppm is ≤ 1. (b) As of June 15, 2005 EPA revoked the 1-hour ozone standard in all areas except the 8-hour ozone nonattainment Early Action Compact (EAC) Areas.

2.3.5 National ambient air quality standards (NAAQS) for particle pollution

To protect public health and welfare, EPA issues National Ambient Air Quality Standards (NAAQS) for particulate matter. EPA first issued standards for particulate matter in 1971; and revised the standards in 1987 and 1997. In September 2006, the Agency revised the 1997 standards. The Clean Air Act established two types of national air quality standards for particle pollution. Primary standards set limits to protect public health, including the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards set limits to protect public welfare, including protection against visibility impairment, damage to animals, crops, vegetation, and buildings.

The nation's air quality standards for particulate matter were first established in 1971 and were not significantly revised until 1987, when EPA changed the indicator of the standards to regulate inhalable particles smaller than, or equal to, 10 micrometers in diameter (that's about 1/4 the size of a single grain of table salt).

Ten years later, after a lengthy review, EPA revised the PM standards, setting separate standards for fine particles ($PM_{2.5}$) based on their link to serious health problems ranging from increased symptoms, hospital admissions and emergency room visits for people with heart and lung disease, to premature death in people with heart or lung disease.

The 1997 standards also retained but slightly revised standards for PM_{10} which were intended to regulate "inhalable coarse particles" that ranged from 2.5 to 10 micrometers in diameter. PM_{10} measurements, however, contain both fine and coarse particles.

EPA revised the air quality standards for particle pollution in 2006. The 2006 standards tighten the 24-hour fine particle standard from the current level of 65 micrograms per cubic meter (µg/m^3) to 35µg/m^3, and retain the current annual fine particle standard at 15µg/m^3. The Agency decided to retain the existing 24-hour PM_{10}

standard of 150µg/m^3. The Agency revoked the annual PM_{10} standard, because available evidence does not suggest a link between long-term exposure to PM_{10} and health problems.

The Clean Air Act requires EPA to review the latest scientific information and standards every five years. Before new standards are established, policy decisions undergo rigorous review by the scientific community, industry, public interest groups, the general public and the Clean Air Scientific Advisory Committee (CASAC).

Table 2.5 National ambient air quality standards for particle pollution

Pollutant	Primary Standards	Averaging Times	Secondary Standards
Particulate Matter (PM_{10})	Revoked (1)	Annual (1) (Arith. Mean)	
	150 µg/m^3	24-hour (2)	
Particulate Matter ($PM_{2.5}$)	15.0 µg/m^3	Annual (3) (Arith. Mean)	Same as Primary
	35 µg/m^3	24-hour (4)	

Units of measure for the standards are micrograms per cubic meter of air (µg/m^3).
Footnotes:

(1) - Due to a lack of evidence linking health problems to long-term exposure to coarse particle pollution, the agency revoked the annual PM_{10} standard in 2006 (effective December 17, 2006).

(2) - Not to be exceeded more than once per year on average over 3 years.

(3) - To attain this standard, the 3-year average of the weighted annual mean $PM_{2.5}$ concentrations from single or multiple community-oriented monitors must not exceed 15.0µg/m^3.

(4) - To attain this standard, the 3-year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 35 µg/m^3(effective December 17, 2006). (http://www.epa.gov/air/criteria.html)

2.3.6 Thailand standards for particle pollution

Thailand, the Ministry of Interior has announced the during safety in industrialization 8-hour PM_{10} standard at 5 mg/m^3 (500µg/m^3), and the total dust standard at 15 mg/m^3 (1500 µg/m^3).In 1995, the PCD has announced the 24-hour PM_{10} ambient air quality standard at 0.12 mg/m^3 (120 µg/m^3), and the annual standard at 0.05 mg/m^3 (50 µg/m^3). The 24-hour total dust standard at 0.33 mg/m^3(330 µg/m^3), and the annual standard at 0.10 mg/m^3 (100 µg/m^3). (www.pcd/air quality and noise standard. html.)

2.4 Control of indoor air quality (IAQ)

The sources of indoor particle pollutants can be divided into indoor pollution sources and outdoor pollution sources, and the concentrations and composition of indoor particle pollutants are different with different pollution sources. In order to provide a comfortable and healthy indoor air environment, measures must be adopted to control the concentration level of indoor pollutants and improve IAQ. Control of indoor air pollution mainly include on there general process: control of pollution sources, ventilation and indoor air purification or air cleaning.

2.4.1 Control of pollution sources

Control of pollution sources is a most economical and effective approach in improving IAQ to eliminate or reduce indoor pollution sources (Guo, *et al*., 2003). The best ways of controlling indoor air pollution are to use pollution-free or low-pollution materials and to adopt the design and maintenance measures that avoid producing indoor pollutants. They are outlined in detail in the following (Li, *et al*., 2004)

- Filtrating the outdoor air to prevent outdoor pollutants from entering the room.
- Isolating the sites that may form pollution sources (e.g., copycat rooms, printer rooms, kitchen and toilet) in order to avoid intercrossing infection, and using the enforced ventilation when necessary.
- Making full use of pollution-free or low-pollution building materials and decorating materials. Preventing building products with high pollution from entering market by government legislating and setting up industry standard. For the products in markets, government can label them with different grade. The building materials and decorating materials with high pollution can be eliminated by marke mechanism.
- Dust and liquid drops are the important medium for bacteria to spread. It is necessary to termly clean the components that are easy to be infected in air-conditioning systems (e.g., filter, heat exchanger and muffler) and to replace them in time in order to avoid the aggradations of pollutants.

Moreover, the condensing water should be eliminated in time or ICTHS is employed in air-conditioning systems to prevent bacteria from propagating. In addition, occupants' behavior is also an important origin for indoor pollutants, so we should form better customs such as no high strength activities in room, keeping better individual sanitation, no smoking in room, and avoiding using pressurized spray and cosmetic.

Removing indoor pollutant sources form the indoor environment and replacing them with non-polluting substitutes can directly and substantially improve indoor air quality. Successful use of this strategy requires sacrificing the function of source materials or finding suitable substitutes. Therefore, decisions to remove and substitute for pollutant source require a careful balancing of economic, functional, and health concerns.

Some sources of indoor air pollution that cannot be easily removed or replaced can be controlled by encapsulation or confinement. These processes do not eliminate potential pollution source, but rather restrict the movement of the pollutants of concern in the indoor atmosphere.

Properly operating and maintaining appliances and products can also reduce their emissions of indoor air pollutants. This control strategy can include turning or cleaning sources to reduce pollutant generation or curtailing source use or shifting source use in time and space in order to separate emissions from human activity and there by reduce human exposure.

Many product- related sources of indoor air pollutants can be modified to reduce their contaminant emissions. Some of these modifications can be carried out by the manufacturer while others may take place at the location of source use. Source control of indoor air pollution such as combustion appliances and tobacco smoking are discussed below.

2.4.1.1 Combustion appliances

Combustion appliances: Pollutant emissions from combustion appliances can be controlled through exhaust ventilation, confinement, proper operation and maintenance, and burner modification.

Combustion pollutants can be controlled by venting flue gases. Confining combustion appliances to specially partitioned rooms or compartments prevents them from polluting the larger, general-use habitable space. In addition, combustion appliances burn more cleanly (i.e., emit reduced quantities of pollutants) if kept properly adjusted and cleaned through appropriate maintenance.

A number of manufacturer modifications to combustion appliances have resulted in cleaner emissions. Advances in gas burner technology may improve appliance performance by reducing the rate of pollutant formation. For example, tests have shown that inserts for burners in gas ranges, ovens, and other appliances reduce emissions of combustion gases and particulate. Also, replacing pilot lights with electronic ignition for gas burners eliminates the continuous low-level emission of combustion performance of, and reduced the leakage of combustion products from these appliances into the indoor air.

2.4.1.2 Tobacco smoking

Tobacco smoking: Pollutant emissions from tobacco smoking can be controlled by its source, tobacco smoking from indoor environments or confining tobacco smoking to designated spaces apart form general habitable areas. Effective control of pollutant by source confinement requires that designated smoking areas be depressurized and vented directly to the outside. Smoking restrictions have been most widely applied to pubic buildings and public areas of buildings, but are becoming increasingly used in private spaces.

2.4.2 Ventilation

Ventilation is essential for the maintenance of good indoor air quality. However despite its essential need there is much evidence to suggest that energy loss through uncontrolled or unnecessary air change is excessive and that much can be done to minimize such loss. Considerable losses may also be associated with ventilating pollutants that can be more effectively controlled by their elimination at the source. Air infiltration exacerbated by poor building air tightness adds further to the lack of control and energy waste. The relative importance of building energy consumption in developed countries is show building energy demand of comparable significance more than twice that of industrial demand.

Natural ventilation: occurs when door and windows are open. This method is extremely effective in reducing pollutant levels when short- term activities, such as cooking or cleaning, are taking place. The air flow rate through the house is often increased by opening door or windows for cross-ventilation. The main disadvantage of natural ventilation is the increased energy cost associated with extra heating or cooling load (Geros, V., *et al*., 1999). Alternatively, passive cooling techniques present a very important alternative to conventional air conditioning of building. The development of efficient passive cooling techniques is a first priority for building scientists Recent research has show that night ventilation techniques, when applied to massive buildings can significantly reduce the cooling load of air conditioning buildings and increase the thermal comfort levels of non-air-conditioning buildings.

Night ventilation: night techniques are based on the use of the cool ambient air as a heat sink, to decrease the indoor air temperature as well as the temperature of the building's structure. The cooling efficiency of these techniques is mainly based on the air flow and thermal mass.

Night techniques can contribute to decrease significantly the cooling load of air conditioning and improve the comfort levels of free-floating buildings. The exact contribution of night ventilation for a specific building is function of the building structural and design characteristics, the climatic conditions and the building's site layout, the applied airflow rate, the efficient coupling of airflow with the thermal mass of the building, and the assumed operational conditions. Appropriate design of night ventilation systems requires exact consideration of all above parameters and optimization of the whole procedure by using exact thermal and airflow simulation codes.

Prominent airflow distribution as well as outstanding air condition systems is necessary in order to achieve a comfortable and healthy environment in occupied zone. Air supply mode is the main influence factor of airflow distribution. Ventilation is mainly focused on displacement ventilation (DV), personalized ventilation (PV) and under-floor air distribution (UFAD).

2.4.2.1 Displacement ventilation (DV)

A displacement ventilation system differs from the more typically observed turbulent mixing system primarily by how it moves the air through the occupied space. The measure of how a give geometry of supply diffusers and exhaust grilles removes the air contaminants in a space is referred to by the term ventilation effectiveness (Skaaret, 1984).

One of the basic advantages of DV system approach is that in many situations it can be more efficient in terms of the removal of air contaminants than a turbulent mixing ventilation system for a give quantity of air. One key difference between the approaches is the amount of mixing that is intended to occur between the conditioned supply air entering the space, and the air that is in the room and has already begun to be come contaminated from sources within the space.

The achievement in ventilation effectiveness is a function of the following parameters: the location of the components that deliver supply air and remove air from a space, the relative temperatures of the air. A review of displacement ventilation (Yuan *et al.*, 1988) indicates that they present certain challenges in terms of thermal comfort. Uncomfortable conditions can occur if the temperature at the foot level is significantly lower than at the head level.

Unlike more traditional mixed-air systems where the goal of the supply-air diffusers is to achieve rapid mixing of the delivered supply air with the room air, the goal in displacement ventilation systems is to have as little mixing as possible. In one approach to achieving displacement ventilation, the supply air is released low in the space, either at the corners or from the floor, and the air is removed from the space at the ceiling. In addition, the air is introduced at a temperature slightly below that of the space so that it can slowly push the air up through the space as the air increase in temperature around heat sources such as people, electrical equipment, and lights.

Displacement ventilation is a new type of air supply mode, and it only improves the environment in occupied zone and not all the spaces. Hence DV not only saves much energy but keeps better IAQ. Indoor airflow pattern and distribution profiles of temperature and contaminant concentration are shown in Fig. 2.6. Air temperature is rather uniform at horizontal level except in the region near the air supply diffusers. Vertical temperature gradients always exist in the space with DV system and they are not linear in all the space height. DV, compared with mixing ventilation (MV), has higher ventilation efficiency and IAQ due to its piston flow effect and temperature stratification. However, DV may not provide better IAQ than MV if the contaminant sources are not associated with heat sources, such as VOCs from building materials (Lin, *et al*., 2005, and Cheong *et al*., 2006). Additionally, DV system is not suitable for removing ground level contaminants, or where the main contaminants are emitted at the ground level, because the contaminants would simply be displaced into the breathing zone. For gaseous contaminants, the displacement effect of DV system is probably dependant on the molecular weight of contaminants. Since VOCs have greater mass, the displacement effect is significantly less than that for CO_2. There are many factors that affect the design and the performance of DV system. The door and window have significant effects on the displacement effectiveness of DV system (Lin, *et al*., 2007). The displacement effectiveness for CO_2 and VOCs are significantly reduced by the door opening due to the change in airflow pattern. The added momentum from the incoming air causes pollutants to be displaced into the breathing zone. The lateral displacement of the air due to the window heat transmission may result in disruption of the displacement effect, which reduces the effectiveness of DV system in removing contaminants. The influence of furniture is related to the location and distribution. Furniture has minimal impact on thermal comfort and IAQ when they do not obstruct the airflow from diffusers (Lau and Chen, 2007). Stratification boundary is the interface between the upper mixing zone and the lower zone with unidirectional flow. The air of occupied zone will be sanitary only when the height of the stratification boundary is above the occupied zone. Therefore, the height of the stratification boundary is a very important parameter in DV system. Lee and Lam (2007) calculated the height by simulation and found that with a room height of 2.4 m and design room temperature of 25.5 °C (defined at 1.1m above floor level), under the normal load to airflow ratio of 12,000 Wm^{-3} s and minimum supply temperature of 18 °C, the height was 2.2 m, and was above normal breathing level. There are many factors that affect the height. The height decreased as the room load increased, but the height increased as the room load increased further when the room load was greater than about $45Wm^{-2}$ (Xing, and Awbi, 2002). The height increased as the flow rate increased for a given heat source at a fixed surface temperature. For a fixed flow rate and a given heat source diameter, the height decreased as the heat source temperature increased (Bouzinaoui, *et al.*, 2005). DV system is quite suitable for large size room due to its stratification characteristics. Future research could explore the possibility to apply DV system in ordinary rooms.

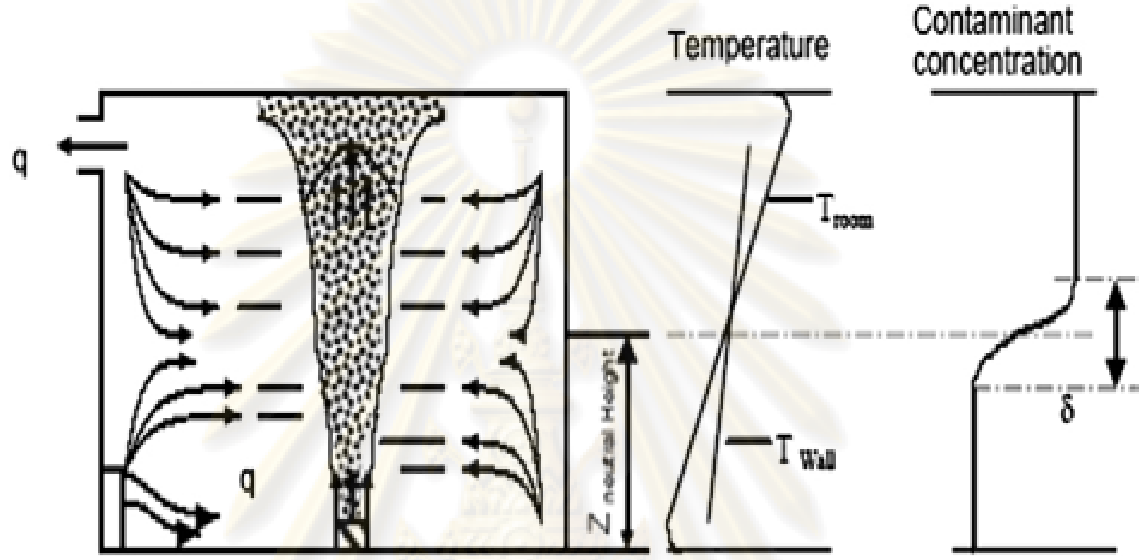


Fig. 2.6 Indoor airflow pattern and distribution profiles of temperature and contaminant concentration. (Lin, *et al*., 2005)

2.4.2.2 Personalized ventilation (PV)

Personalized ventilation is a special displacement ventilation system, and it really embodies the central status of occupants. PV is able to provide occupants with improved IAQ, thermal comfort and individual control of the micro-environment. Through adjusting the personalized airflow rate, direction, temperature and turbulence intensity, occupants can achieve their preferred individual microenvironment, which is impossible in conventional air conditioning systems. There are many types of PV system. For the desk-edgemounted PV system, it was possible to obtain an air change effectiveness of approximately 1.5 when the supply flow rate was 3.5–6.5 l s^{-1}, which represented a 50% increase in effective ventilation rate at the breathing zone (Faulkner, *et al*., 2004). Niu, *et al*., 2007 proposed a chair-based PV system in Fig. 2.7 and the position of the fresh air supply nozzle can be adjusted by the seated user. The experimental results showed that up to 80 % of the inhaled air could be composed of fresh personalized air with a supply flow rate of less than 3.0l s^{-1}. Perceived air quality was improved greatly by the chair-based PV system. Zhao and Guan, 2007 investigated the dispersion characteristics of particles with aerodynamic diameter of 0.5 – 10 mm in a room ventilated by a PV system by computational fluid dynamics (CFD). The results showed that PV was effective to remove particles smaller than 2 mm, and that PV might not be the best ventilation mode for particles bigger than 7.5 mm due to resulting obvious particle accumulation on the floor. Compared with total volume ventilation, PV is advantageous for many practical applications.

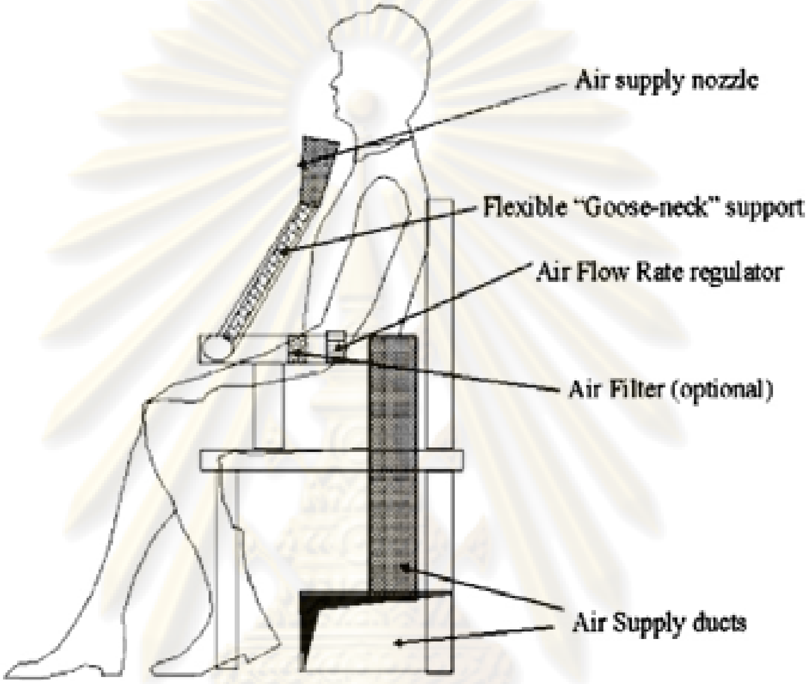


Fig. 2.7 Schematic diagram of chair-based Personal ventilation system (Niu, *et al*., 2007)

2.4.2.3 Under-floor air distribution (UFAD)

Under-floor air distribution system is a new type of air supply mode with the advantages of better flexibility, energy saving and improvement of IAQ (Webster, *et al*., 2002). Its operating principle is shown in Fig. 2.8 Now it has been applied in Europe, Hong Kong, Japan, South Africa and America. At present, the studies on UFAD are focused on its airflow characteristics, IAQ, thermal comfort, thermal characteristics of under-floor plenum, and system energy consumption. Under-floor plenum is one of the most important parts of UFAD. Linden, *et al.*, 2004 suggested that the flow in the plenum be regarded as 2-dimension flow for plenum with small ratio of height to length.

UFAD needs to be researched further in several aspects: individual control of thermal comfort, thermal characteristics of under-floor plenum, development of new types of diffusers, impact of radiation on thermal comfort and indoor airflow characteristics, load calculation, and system control.

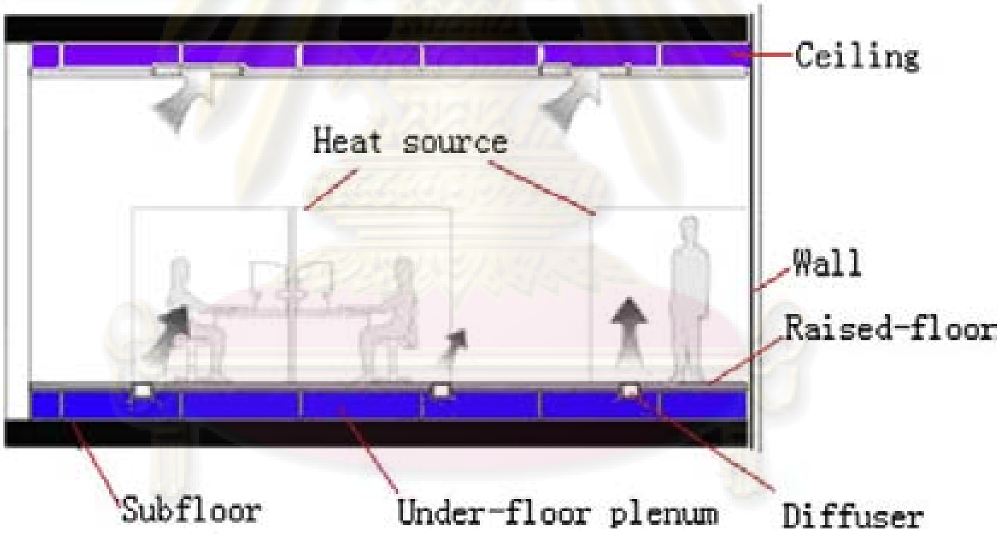


Fig. 2.8 Principle of Under-floor air distribution (Webster, *et al*., 2002).

2.4.3 Air Cleaning

Air cleaning should play an important role in mitigation and prevention of IAQ problems. Particles are always present in indoor air, either coming form interior source or brought in with infiltrating air. Air-cleaning devices remove many of the particles in the air passing through them, thus effectively reducing the total number of preventing lint and other debris form plugging heating and cooling coils to removing particles as small as a few tenths of a micrometer, which could potentially cause a short circuit on a microchip.

Particle removal by filters, Electronic air cleaners, Cyclones, and Scrubbers

Two of the most important performance parameters for particle removal devices are energy cost and particle collection efficiency. While pressure drop reflects the mechanical energy cost to drive airflow through a device, particle collection efficiency shows the effectiveness of the device. Both parameters depend on types of removal devices, their detailed structure, and operating conditions such as air flow rate. In addition, particle collection efficiency also depends on the characteristics of the particles.

2.4.3.1 Particle Removal by Filters (Fibrous filter)

Fibrous filter will be discussed. It should be noted that the same mechanisms and performance characteristics apply to other types of air filters such as those made of foam or membrane.

Fibrous filters are used extensively for air-cleaning purposes. The fibers are much longer than the filter media layer is thick and tend to lie in or chose to the plane of the filter media. The filter media may be used flat, or folded in various ways to yield a more compact filter. In either case, the fibrous filter can be viewed as an assembly of fibers random in planes perpendicular to the direction of flow. Fibrous filters may contain fibers with size form as large as dozens of micrometers to as small as about 0.1 µm. Solidity of filter media is the fraction of the total volume of the sheet that is solid. The solidity of a typical filter media ranges from about 30 percent to as low a 1 percent. The common types of fibers are cellulose fibers (wood fibers), glass fibers, and synthetic fibers.

A common misconception is that a filter works like a sieve, that particles suspended in air are removed only when they are larger than the inter fiber space. On the contract, air filtration is very different from the use of screens on air intakes to keep out leaves, birds and other items. Because of their microscopic nature, particles are removed by their collision to fibers. Particles make contact with the fiber surface, particles generally remain attached because of strong molecular force between particles and fibers. Sieving is not a primary mechanism in air filtration, as particles with such size could be easily collected because of the mechanisms. Common filtration mechanisms are listed as follows:

Diffusion: Particles suspended in the air are constantly bombarded by the molecules around them. Thus, they have a random motion around their basic path along the air streamlines, which increases the probability of the particles contacting fibers and being collected. At atmospheric pressure particles smaller than about 0.2 µm have significant deviations from their streamlines, making diffusion an effective filtration mechanism. Diffusion is a sensitive function of velocity. Lower velocity means more time for particles to move away form their streamlines, and thus an increased probability for the particles to be captured.

Interception: Even if particles follow the airstream exactly, they could make contact with the fibers because of their finite physical sizes. This process has little dependence on velocity, and is effective for particles larger than about 0.5 µm.

Inertial impaction: Particles in air that either are heavy or are at high velocity have significant inertia. In this case, they have difficulty following the airstream bending around fibers, and thus make contact with the fibers and are collected. Inertial impaction is generally effective for particle larger than about 0.5 µm depending on air velocity and fiber size.

Capture by electrostatic force: Under some circumstances, particles or filter media may be intentionally or unintentionally charged; thus electrostatic force may play a role in particle collection. Charged particles will be attracted to fibers with opposite charges by columbic force. If either particles or fibers are charged, particles will be attracted toward the fiber at close range by image force, which are weaker than columbic force. External electrical fields may be applied; thus' charged particle will acquire additional cross-flow motion that leads to higher filter efficiency. Similar to diffusion, low velocity enhances collection by electrostatic force.

Diffusion is very strong for particles smaller than a few ten of a micrometer; interception and inertial impaction are very effective for particles larger than about 0.5 µm. Because of these opposing trends, there is a minimum efficiency for filter media at a particle size between 0.1 and 0.4 µm, depending on fiber diameter and air velocity.

Filters, depending on fiber diameter, media thickness, and packing density, could have a minimum efficiency ranging from a few percent for low-efficiency filters to 99.97 percent for high efficiency particulate air (HEPA) filters or considerably higher. Although particles generally stick to fibers after making contact, there are exceptions. When a heavy particle traveling at high velocity hits a fiber, it may bounce off. Particle bounce depends on the particle's mass, velocity, direction relative to fiber, and fiber size. In addition, bounce is a very sensitive function of hardness and elasticity of fiber and particle. Bounce for particles smaller than a few micrometers at velocities lower than 20 cm/s is usually negligible. For applications where particles bounce may be an issue, fibers can be coated with a liquid or adhesive that tends to reduce particle bounce dramatically.

2.4.3.1.1 Filter Type by Collection Mechanisms and Effect of Filer Loading

1.) Mechanical filters

Mechanical filters: Filters that collect particles through mechanical mechanism (diffusion, interception, and inertial impaction) without the influence of electrostatic forces are called *mechanical filter*. As particles are captured by filters, they become part of filter structure. Collected particles increase the pressure drop as they provide resistance to airflow, and contribute to filter efficiency as they become particle collectors as well. The loading process of fibrous filters is typically classified as two stages: depth loading and surface loading. Initial deposition of particles generally occurs in the depth of filter media. As more particles are collected in the filter medium, the top layer of the filter medium becomes very efficient and particles start to bridge across the medium surface. Eventually, particles will deposit on the filter medium surface in a cake form.

2.) Electrically charged fibrous filter (electrets)

The advantage of materials of this type is that the charge on the fibers considerably augments the filtration efficiency without contributing to the airflow resistance. Particle collection efficiency by electrically charged filters is altered by a combination of two causes. One is the same as that for mechanical filters, efficiency charges due to mechanical means increase. The other is that the deposited material, interacting with the electric charge on the filter, reduces efficiency due to electrical means. The combined effect is complicated as the two processes occur at the entries of particles and fibers, operating condition mechanisms are reduced. Eventually, as enough particles are collected, the efficiency will increase but at the expense of pressure drop

At times, when filters are heavily loaded, subject to unstable operating conditions or external force, chunks of particles already collected could become loose and penetrate through the filter. Particle shedding occurs less frequently when an adhesive coating is used on fibers.

2.4.3.1.2 Filter Types by filter media and construction

They are four basic types:

1) Flat-panel filter

Fare air filters in which all filter media in the same plane; thus the face velocity and media velocity are the same. Face velocity is the velocity of the air approaching the filter; the media velocity is the air velocity approaching the medium.

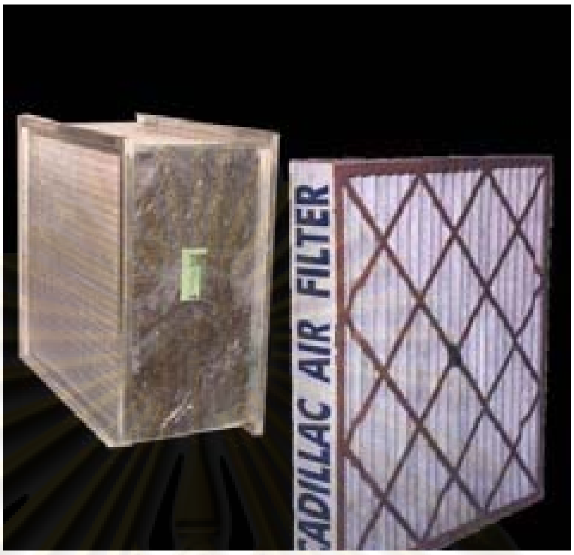


Fig. 2.9 Flat-panel filter

2) Pleated-panel filter

Pleated filters use an extended filter media area to make the media velocity much lower than face velocity; thus they typically have much higher filter efficiency at acceptable pressure drop. Typical pleat depths range form 1 to 2 in.

Fig. 2.10 Pleated-panel filter

3) Bag or pocket filter

The non supported mat filter is one of the most popular designs for high efficiency air filter used today. When air flows through bag filters, the filters expand, exposing all the media to the airstream.

Fig. 2.11 Bag or pocket filter

4) Moving-curtain or renewable media filter

Renewable filters are devices in which clean filter media are unrolled at one end, exposed to a dirty airstream. It is advanced at intervals to keep the pressure drop through the exposed airstream within a desired operating rang. Dirty media are rolled a take up reel at the other end of the filter.

Fig. 2.12 Renewable media filter

2.4.3.2 Particle Removal by Electronic Air Cleaners

An electronic air cleaner is a device that collects particles suspended in gas stream as a result of electrical precipitation. Fig. 2.13 Electronic air cleaners are also referred to as *electrostatic precipitators* (ESPs). Common electronic air cleaners consist of ionizing and collecting parts arranged sequentially or combined in a single stage. The air passes between parallel plates. Between these plates, equally spaced wires serve as high voltage electrodes. When air passes through the inter-electrode space, the ions produced by corona discharge charges the particles. Then the electric field drives the particles either to the grounded plates or to specially designed collecting plates.

When the collector plates are loaded with dust, the efficiency of the electronic cleaner is reduced, sometimes dramatically, which is frequently indicated by acing between oppositely charged plates. The collector plates can be cleaned in place auto metrically or manually or can be cleaned after removal by washing, or “rapping”. Because of the decreased efficiency during its operation, initial efficiency may not be a good indicator as to how the electronic air cleaner performs. Instead, frequency of cleaning or maintenance may be more important. Unlike cyclones and filter, the major energy consumption of an electronic air cleaner comes form the electric energy used to ionize the air rather than the pressure drop across its structure.

Fig. 2.13 Electronic air cleaner

2. 4.3.3 Particle Removal by Inertial Separators, Cyclones, and Louvers

Inertial separators turn the airflow and use the inertia of the particles to separate them from the airstream. See Fig. 2.14 and Fig. 2.15 for cyclone and louver picture, respectively.

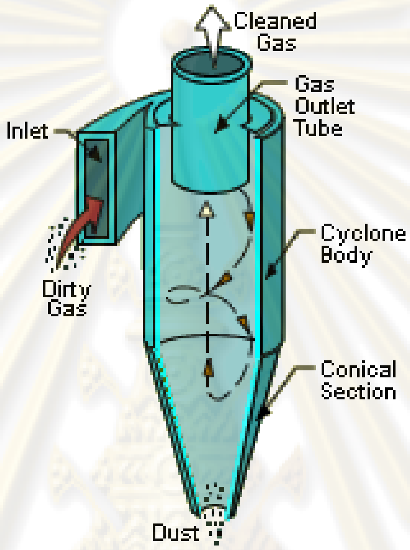


Fig. 2.14 Cyclone

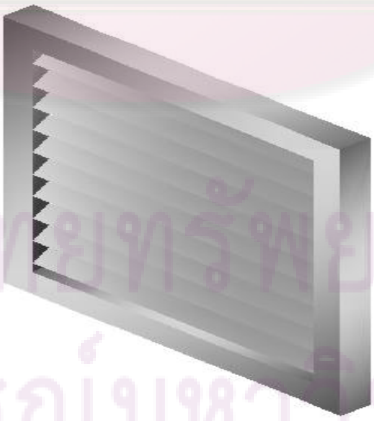


Fig. 2.15 Louver

Inertial devices remove only coarse particles. Their value is mainly for the removal of coarse dust, raindrops, and other material from large volumes of air where a small residue is unimportant, or as a pre-separator before passing through more efficient filters.

Louvers are used extensively in air intakes and may be used in other applications such as removing grease from kitchen exhaust is high concentration of aerosol.

2.4.3.4 Scrubbers

An air scrubber is used to clean air or other gases of various pollutants and dust particles by mixing the polluted gas with a water mist. The dirt and pollutants are encased by the water particles and when the mixture is condensed the pollutants stay in the water while the gas rises up and can be put back into circulation.

Scrubbers collect particles on liquid droplets that are sprayed into the airstream and then remove them. Scrubbers are used primarily in specialized industrial air cleaning such as paint booths and cleaning of power plant exhaust.

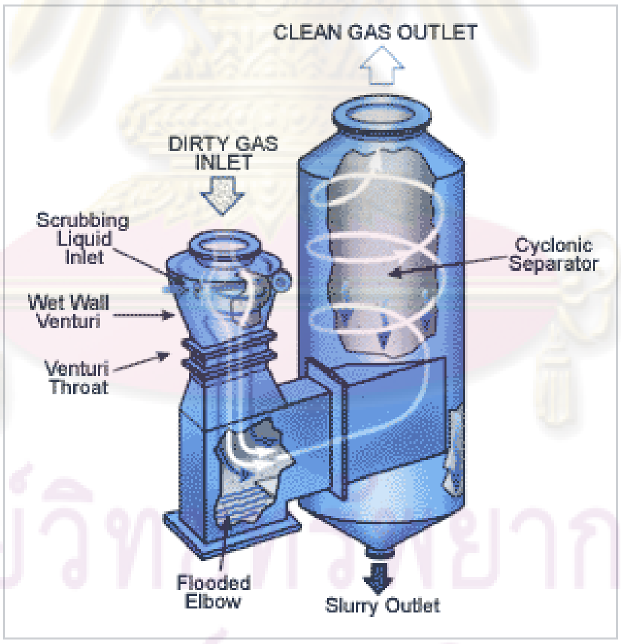


Fig. 2.16 Scrubber

CHAPTER III

METHODOLOGY

3.1 Research overview

The main objective of this study is to synthesize silk fibroin (SF) fibers for indoor air particulate matter removal**.** They were degummed with 0.5 % wt sodium carbonate (Na_2CO_3), and were studied the characterization, physical properties, and mechanical properties. The SF fiber was studied the efficiency of particulate matter removal by the effect of air flow rate and initial PM concentration. Research flow chart can be illustrated in **Fig. 3.1.**

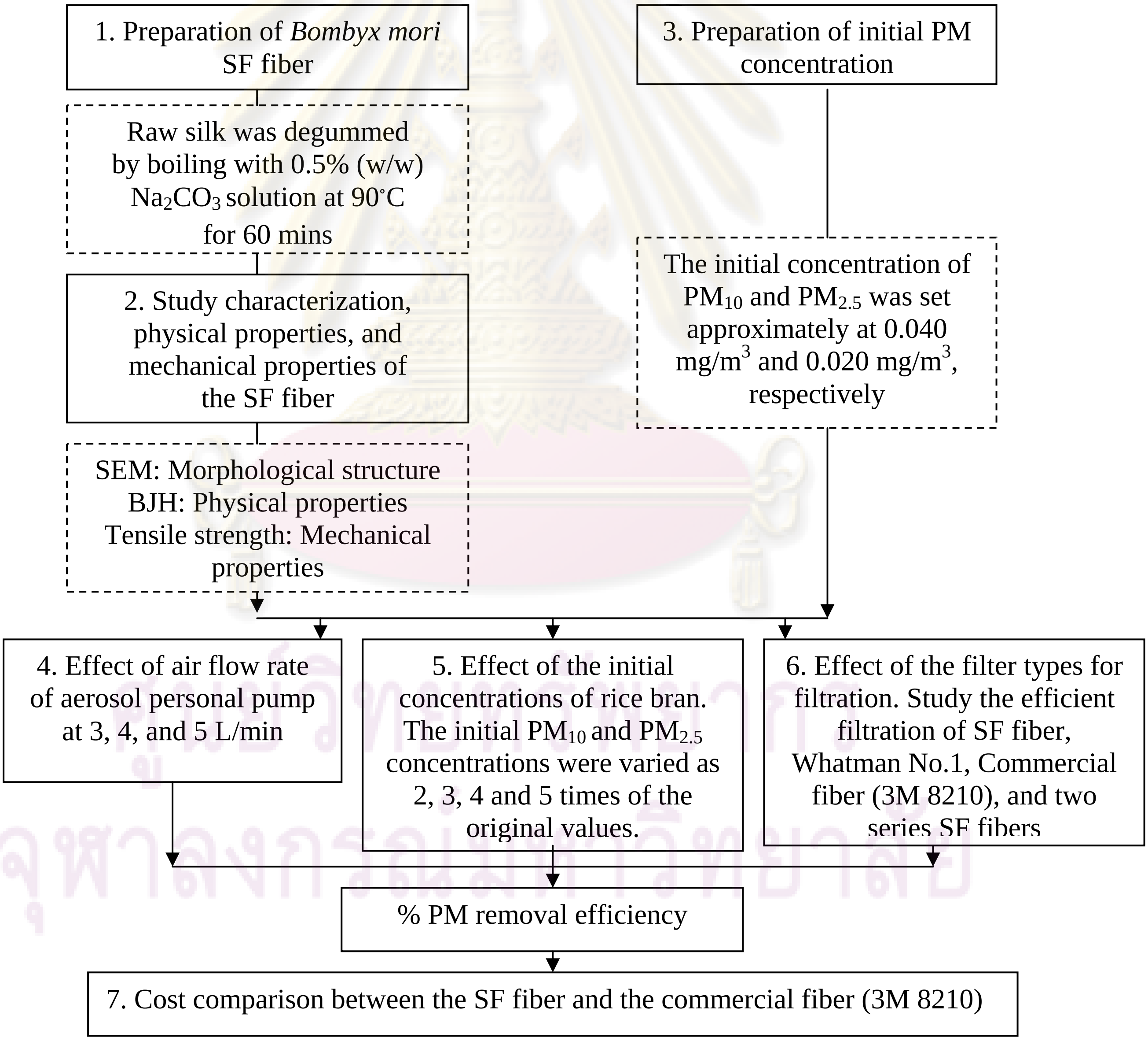


Fig. 3.1 Flow chart of the research

3.2 Instrument and equipment

1) Small fan

In this study, the small fans (220V) were used for mixing the particle of rice bran as shown in Fig. 3.2. They were installed in the reactor to ensure adequate mixing of rice bran particulate matter in air.

Fig. 3.2 Small fan

2) Hygrometer monitor

Hygrometer monitor (Model TEPEL 550) was installed in the reactor that it was continuously monitored for measurement the temperature and relative humidity as shown in Fig. 3.3. This instrument is a portables 3.5 digit, compact-sized digital Thermo-Hygrometer designed for simplicity one hand operation. Use platinum resistance temperature detector Pt385/1000Ω (Alpha=0.00385) as temperature sensor, and use thin film polymer capacitive type relative humidity sensor as hygrometer sensor.

Fig. 3.3 Hygrometer monitor (Model TEPEL 550)

3) Aerosol personal pump

The aerosol personal pump was used for pump the PM pollutants in the reactor through the SF filter as shown in Fig. 3.4. It can be set the air flow rate. In this work, study the effect of air flow rate of aerosol personal pump that it was fixed at 3, 4, and 5 L/min. The maximum flow rate of aerosol personal pump is 5 L/min.

Fig. 3.4 Aerosol personal pump

4) Side pak personal aerosol monitor (AM510)

Model of the side pak personal aerosol monitor (AM510) is designed to accept impactors (size-elective inlets) to attain specific mass fractions of the sampled aerosol. In this study, the PM concentrations were continuously measured using the side pak personal aerosol monitor (AM510) with the PM $_{2.5}$, and PM$_{10}$ impactor as shown in Fig. 3.5. The results are displayed as in unit of mg/m^3. The standard inlet on the side pak personal aerosol monitor (AM510) was designed not to cause any specific particle size separations. It is intended for use with external size-selective aerosol samplers such as cyclone or external impactor at any flow rate within the allowable range.

Fig. 3.5 Side pak personal aerosol monitor (AM510)

4) Impactor

The side pak personal aerosol monitor (AM510) kits include a set of three impactors that can be used in place of the standard inlet to conveniently separate specific particle size frations. The 50% cut-off size is marked in micrometer (μ) on each impactor. The three impactors provide cuts at *1.0μ, 2.5μ,* and *10μ,* corresponding to PM_1, $PM_{2.5}$, and PM_{10} specifications respectively. All inlets are made of conductive plastic to eliminate particle losses due to static charges as shown in Fig. 3.6.

5) Cyclone

The cyclone accessory provides with the side pak personal aerosol monitor (AM510) kit is designed to provide a cut-off at 4 μm. This is specified as a 50% cut-off size at 4 μm as shown in Fig. 3.6.

Fig. 3.6 Impactors and cyclone

6) Scanning electron microscope (SEM)

SEM characterization was performed by using a Jeol JSM-5410LV microscope, at an acceleration voltage of 15kV as shown in Fig. 3.7. SF fiber samples for SEM was cryogenically fractured in liquid nitrogen and then mounted onto aluminium specimen stubs by means of double-sided adhesive tape and sputter-coated with a thin gold layer under rarefied Argon atmosphere.

Fig. 3.7 Scanning electron microscope (SEM : Model Jeol JSM-5410LV)

7) Barrett Joyner Halenda (BJH) nitrogen adsorption technique

Physical properties of SF fiber samples were examined using the Autosorb-1(AS1Win Version 1.50) as shown in Fig. 3.8. Nitrogen gas was utilized as an adsorbate gas. The sample was degassed by setting the desired temperature at 60 ºC. The saturated vapor pressure of the adsorbate (P_0) is 760 mmHg. The BJH method was applied for specific surface area, specific pore volume, and pore size analysis.

Fig. 3.8 Autosorb-1(AS1Win Version 1.50)

8) Mechanical testing

The mechanical properties of the SF fiber were measured. Static uniaxial tension tests was carried out at room temperature by using a universal material test machine LR5K (Lloyd instruments, USA) with pneumatic clamping as shown in Fig. 3.9. The load cell was set at 50 N. The crosshead speed at 100 mm/min, and the gauge length at 200 mm were used. Five specimens of each SF fiber were measured at the same conditions. The force–displacement curves was displayed and then used to determine with stress and strain of the SF fiber.

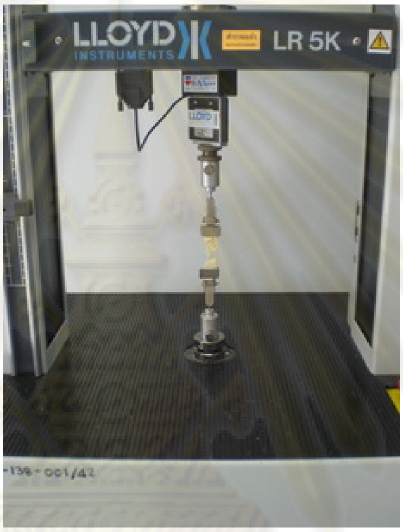


Fig. 3.9 Universal material test machine LR5K (Lloyd instruments, USA)

The stress and strain of the SF fiber can be calculated as follows :

$$\text{Stress } (\sigma) = \frac{F}{W} \qquad (1)$$

where σ = stress (N/mm^2)
F = force (N)
W = the specimen width of the SF fiber (mm)

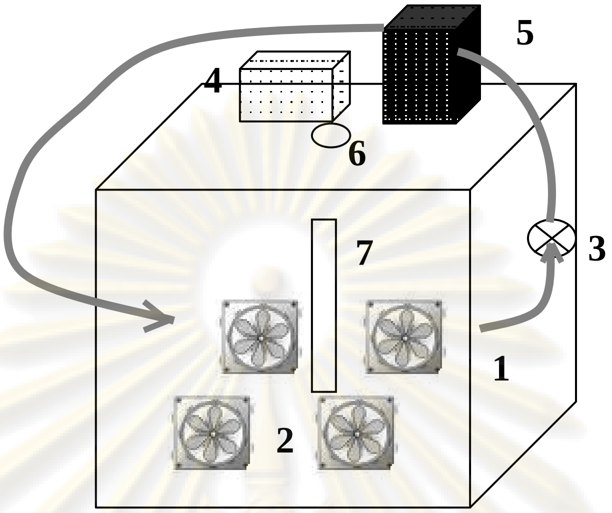
$$\text{Strain } (\varepsilon) = \frac{L - L_0}{L_0} \qquad (2)$$

where ε = strain
L_0 = the initial specimen length of the SF fiber (mm)
L = the final specimen length of the SF fiber (mm)

3.3 The reactor and measurement

Reactor as shown in Fig. 3.10 and Fig. 3.11 shows the schematic diagram of the reactor. As shown in Fig. 3.10 a reactor with the dimensions of 50 cm × 45 cm× 35 cm was used as a reactor in this study. The temperature and relative humidity were continuously monitored by the Hygrometer monitor (Model TECPEL 550). In all sets of experiment, temperature and relative humidity ranged from 25 - 30 ºC and 65 - 70 %, respectively. Rice bran form a local rice mill in Ubonratchathani province was used as indoor air contaminant. Four mixing small fans were installed in the reactor to ensure adequate mixing of rice bran particulate matter in air. Rice bran was added from the top of the reactor and allowed to reach equilibrium. The SF filter was placed inside the filter holder with the diameter of 33 mm. Then, it was connected the reactor and an aerosol personal pump (Fig. 3.10). The PM pollutants in the reactor were pumped through the SF filter using an aerosol personal pump. The PM concentration was continuously measured for 8 hrs by the Side Pak Personal Aerosol Monitor with impactor $PM_{2.5}$ and PM_{10}. The interval time was set at 10 seconds.

Fig. 3.10 Reactor



1. Air flow direction
2. Four small fans
3. Filter holder with SF fiber
4. Side Pak Personal Aerosol Monitor (AM510)
5. Aerosol personal pump
6. Spot for rice bran addition
7. Hygrometer monitor (TECPEL 550)

Fig. 3.11 Schematic diagram of the reactor

3.4 Materials

3.4.1 Chemicals

Sodium carbonate (Na_2CO_3) analytical grade from Merck Chemical Co.

3.4.2 Cocoons of the *Bombyx mori* silkworm

Cocoons of the *Bombyx mori* silkworm was collected from a local farm in Ubonratchatani province, Thailand.

Fig. 3.12 Silk cocoons

3.5 Experimental

3.5.1 Preparation of *Bombyx mori* silk fibroin

Silk cocoons were dried in sunlight and then cut into small length pieces. Raw silk was degummed by boiling with 0.5% (w/w) Na_2CO_3 solution at 90˚C for 60 mins and then washed with distilled water. After that, they were dried at 80˚C for 3 hrs in a vacuum oven.

3.5.2 Preparation of initial PM concentration

Rice bran form rice milling was used as indoor air particulate matter. It was added from the top of the reactor and allowed to reach equilibrium. Four mixing small fans were installed in the reactor to ensure adequate mixing of rice bran particulate matter in air. The initial concentration of PM_{10} and $PM_{2.5}$ was set approximately at 0.040 mg/m^3 and 0.020 mg/m^3, respectively. These values were achieved by varying the amount of rice bran added into the reactor. The PM concentration was continuously measured using the Side Pak Personal Aerosol Monitor equipped with the $PM_{2.5}$ and PM_{10} impactor for $PM_{2.5}$ and $PM_{10,}$ respectively. The results are displayed as in unit of mg/m^3.

3.5.3 Effect of air flow rate of aerosol personal pump

The initial concentration of rice bran was maintained at 0.040 ± 0.005 mg/m^3 and 0.020 ± 0.005 mg/m^3 for PM_{10} and $PM_{2.5}$, respectively. The PM pollutants in the reactor were pumped through the SF filter using an aerosol personal pump. The air flow rate was varied from 3, 4, and 5 L/min. The PM concentration was continuously measured for 8 hrs by the Side Pak Personal Aerosol Monitor with impactor $PM_{2.5}$ and PM_{10}. The interval time was set at 10 seconds.

3.5.4 Effect of the initial concentrations of rice bran

The rice bran was added into the glass room. The initial PM_{10} concentrations were varied as 2, 3, 4 and 5 times of the original values (initial PM_{10} concentrations as 0.080 mg/m^3, 0.120 mg/m^3, 0.160 mg/m^3, and 0.200 mg/m^3, respectively). The initial $PM_{2.5}$ concentrations were varied as 2, 3, 4, and 5 times of the original values (initial $PM_{2.5}$ concentrations as 0.040 mg/m^3, 0.060 mg/m^3, 0.080 mg/m^3 and 0.120 mg/m^3, respectively). The PM pollutants in the room were pumped through the SF filter using an aerosol personal pump. The air flow rate was selected from 3.5.3 that provides the highest removal efficiency. PM concentration was continuously measured for 8 hrs by a Side Pak Personal Aerosol Monitor with impactor $PM_{2.5}$ and PM_{10}. The interval time was set at 10 seconds.

3.5.5 Effect of the filter types for filtration

The Whatman No.1 filter and the commercial fiber (3M 8120) were used for the comparison of PM removal efficiency with two series SF fibers for filtration by controlling initial concentrations at 0.040 ± 0.005 mg/m^3 and 0.020 ± 0.005 mg/m^3 for PM$_{10}$ and PM$_{2.5}$, respectively. The air flow rate was selected from 3.5.3 that provides the highest removal efficiency.

3.6 Calculation of accumulative mass flux PM on filter media

To estimate the accumulative mass flux PM on filter in this study, the following equation was used:

$$\text{Initial mass flux} = \frac{Co \ x \ Q}{A} \qquad (3)$$

$$\text{Final mass flux} = \frac{C \ x \ Q}{A} \qquad (4)$$

$$\text{Accumulative mass flux} = \text{Initial mass flux - Final mass flux} \qquad (5)$$

where C_0 = average initial particulate matter concentration inside the reactor before filtration (mg/m^3)

C = average final particulate matter concentration after filtration for a period of 8 hrs. (mg/m^3)

Q = velocity of air (L/hr)

A = area of filter media (m^2)

3.7 Calculation of PM removal efficiency

To estimate the removal efficiency of the SF fiber in this study, the following equation was used:

Particulate matter (PM) removal efficiency (%)

$$\% \text{ RE} = \frac{C_0 - C}{C_0} \times 100 \qquad (6)$$

where % RE = Percent removal efficiency

C_0 = initial particulate matter concentration inside the reactor before filtration (mg/m^3)

C = final particulate matter concentration after filtration for a period of 8 hrs. (mg/m^3)

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Preparation of *Bombyx mori* SF fiber

Fig. 4.1 shows the SF fiber from preparation of the *Bombyx mori* silkworm. The SF fiber has yellowish color and thin sheet with the thickness of 3.14 mm. Then it was cut in to a diameter of 3.30 cm as shown in **Fig. 4.2**. In **Fig. 4.3** shows the SF fiber that was placed inside the filter holder for filtration air pollutant filtration.

Fig. 4.1 Silk fibroin fiber

Fig.4.2 Silk fibroin fiber after cut

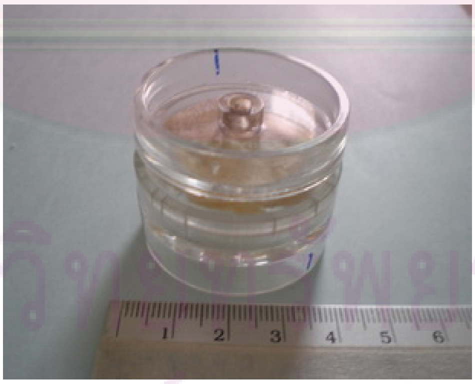
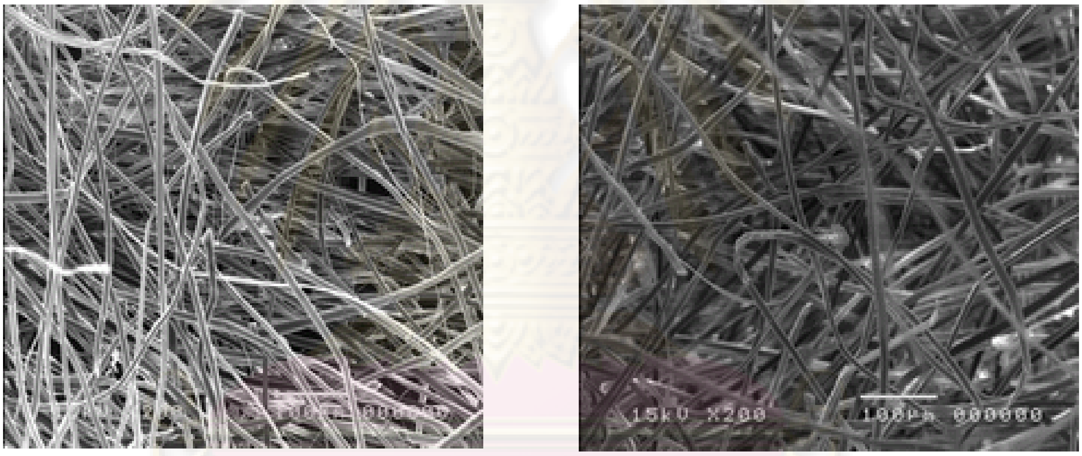


Fig.4.3 Silk fibroin fiber in filter holder

4.2 Study of characterization, physical properties, and mechanical properties of the SF fiber

4.2.1 Morphological structure of SF fiber

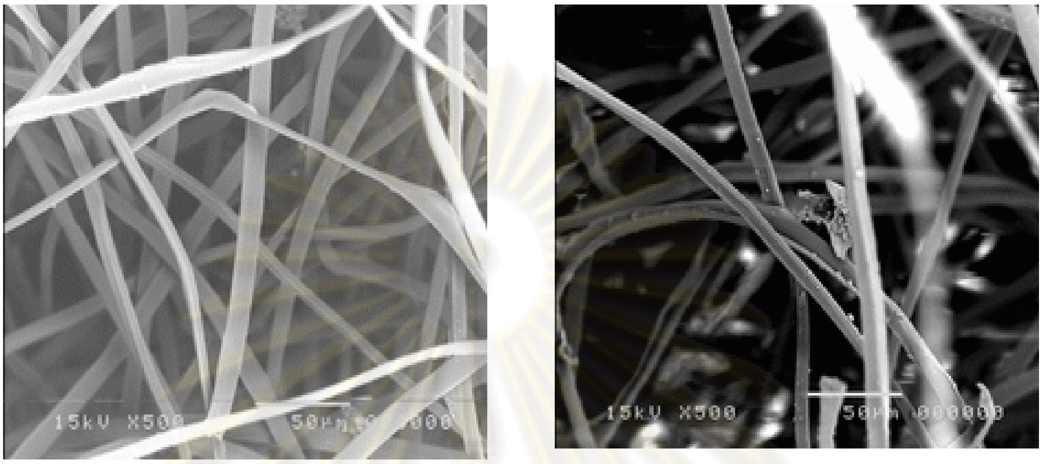
The morphologies of SF fiber (**a**.) before filtration and (**b**.) after filtration at magnifications of 200X, 500X, 1000X, 1500X and 2000X are shown in **Fig. 4.4** to **Fig. 4.8**, respectively. **Fig. (a)** shows the SEM of SF fiber before PM filtration. SEM micrographs revealed the fibrous morphology of the SF fiber. An average diameter of the SF fiber was estimated to be approximately 10 µm. The images of the SF fiber after PM filtration were depicted in **Fig. (b)**. SEM images revealed the deposition of fine particles on the SF fiber. Especially, the morphologies of SF fiber in **Fig. 4.6 (b.)** revealed various sizes of fine particles deposited within fibers. Therefore, the SF fiber may be used as an alternative material for PM filtration.



a) before filtration

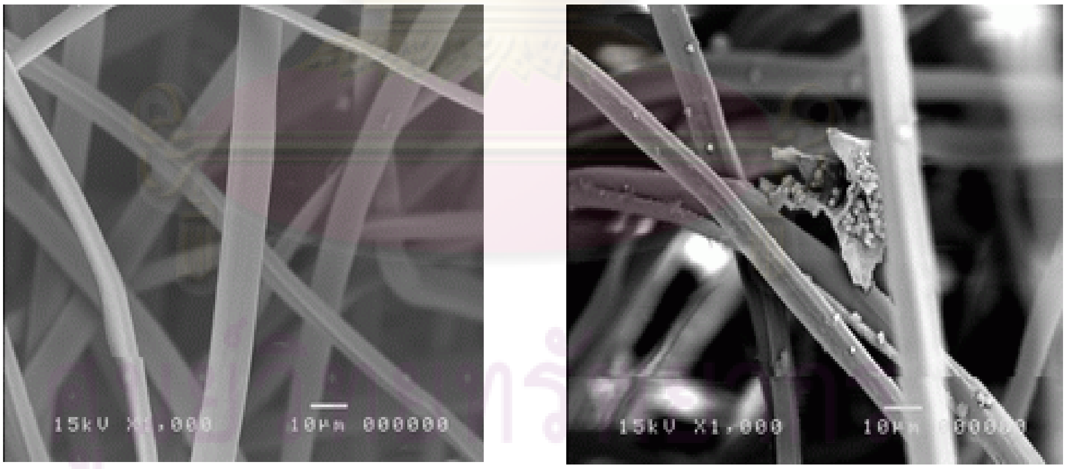
b.) after filtration

Fig. 4.4 The morphologies of SF fiber (a.) before filtration and (b.) after filtration at magnification of 200X



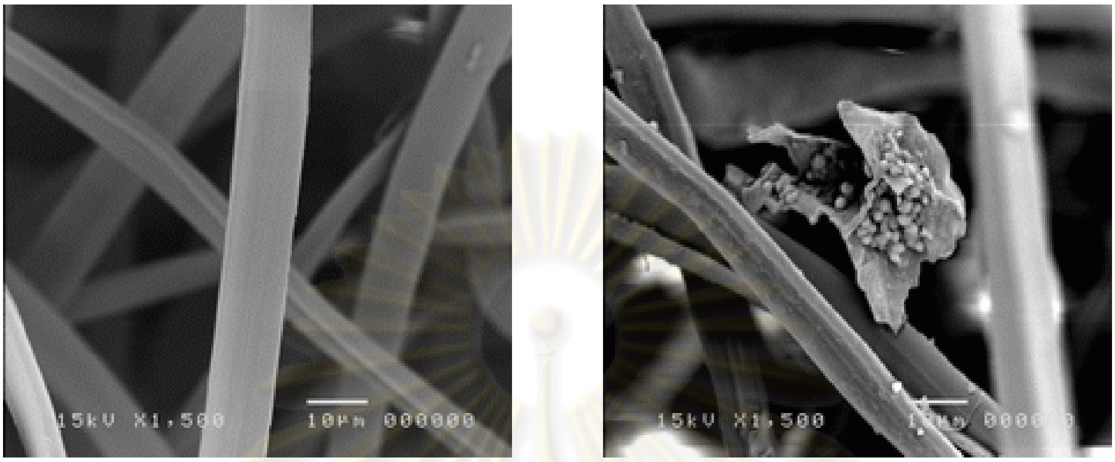
a) before filtration b.) after filtration

Fig. 4.5 The morphologies of SF fiber (a.) before filtration and (b.) after filtration at magnification of 500X



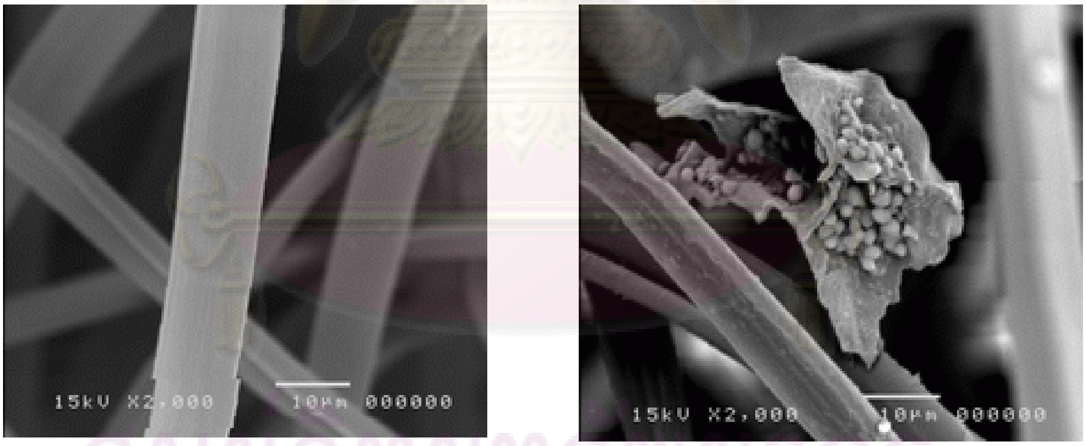
a) before filtration b.) after filtration

Fig. 4.6 The morphologies of SF fiber (a.) before filtration and (b.) after filtration at magnification of 1000X



a) before filtration b.) after filtration

Fig. 4.7 The morphologies of SF fiber (a.) before filtration and (b.) after filtration at magnification 1500X



a) before filtration b.) after filtration

Fig. 4.8 The morphologies of SF fiber (a.) before filtration and (b.) after filtration at magnification of 2000X

4.2.2 Study of physical properties of the SF fiber by BJH method and study accumulative mass flux of PM on the filter media

The accumulative mass flux of PM_{10} on the filter media is shown in **Fig. 4.9.** As seen from the figure, the accumulative mass flux of PM_{10} increased during the initial treatment period and after the 10^{th} hour of treatment. The maximum accumulative mass flux of PM_{10} was received when using the 3M-8210. Moreover, it can be noted that the 3M-8210 fiber has the smallest pore size than the SF fiber when comparison of 5 L/min at air flow rate and also the particle matter can be more attached and accumulated on the 3M 8210 fiber than the SF fiber. However, the 3M-8210 fiber is specifically designed to use as a respiratory protection mask. So fiber of the 3M-8210 must be denser than that of the SF fiber. There for, it could be concluded that the 3M-8210 has the highest accumulative mass flux of PM_{10}.

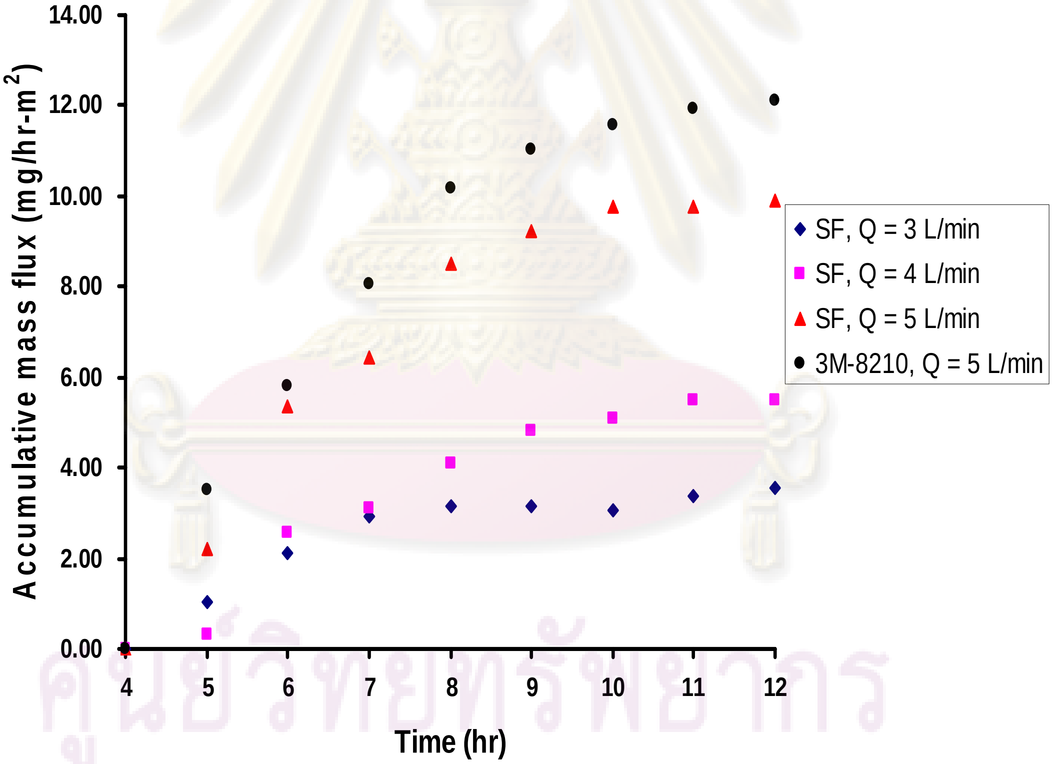


Fig. 4.9 Accumulative mass flux of PM_{10} on the filter media

The accumulative mass flux of $PM_{2.5}$ on the filter media is shown in **Fig. 4.10.** The accumulative mass flux of the SF fiber was studied in different air flow rate. As seen from the figure, the accumulative mass flux of $PM_{2.5}$ increased during the initial treatment period and after the 11th hour of treatment. When using air flow rate of 5 L/min has the highest accumulative mass flux than that of other air flow rate. Moreover, it can be noted that high air flow rate can be more capacity for pump of particulate matter to the fiber. When comparison study of accumulative mass flux of the 3M-8210 fiber and the SF fiber at 5 L/min of air flow rate also shown that the SF fiber has lower accumulative mass flux than the 3M-8210 fiber. It may be conclude that pore size of the SF fiber must be large. So the SF fiber can not be good accumulation of fine particle when compare with the 3M-8210 fiber.

The maximum accumulative mass flux of $PM_{2.5}$ was received when using the 3M-8210. There for, it could be concluded that the 3M-8210 has the highest accumulative mass flux of PM_{10}.

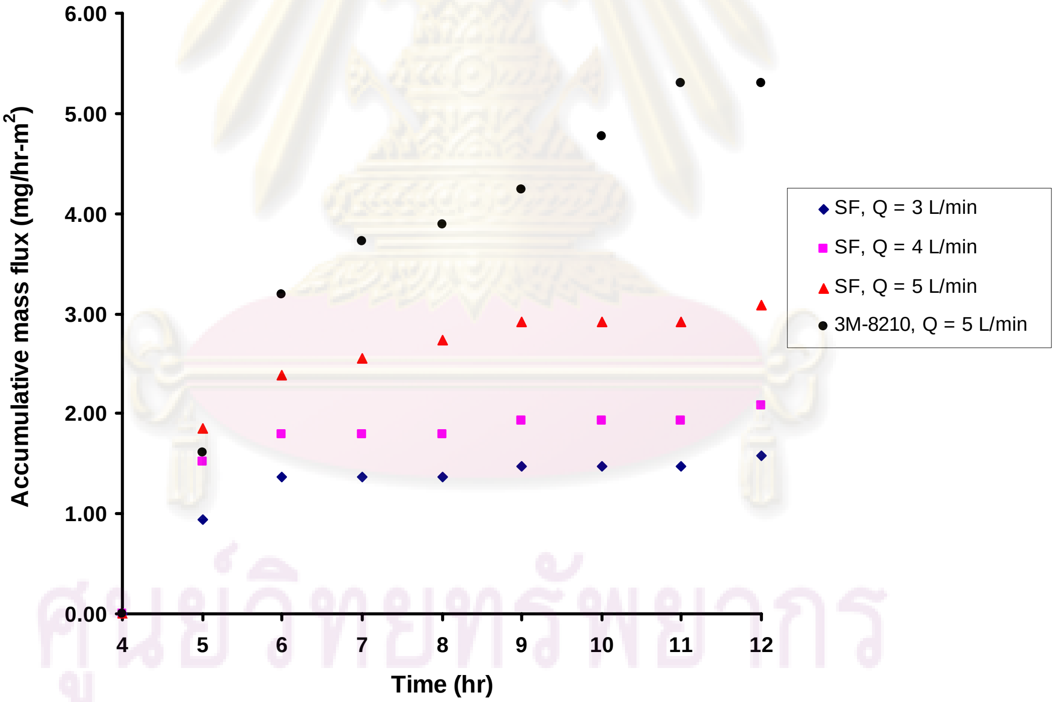


Fig. 4.10 Accumulative mass flux of $PM_{2.5}$ on the filter media

4.2.3 Study of mechanical properties of the SF fiber

In this work, the tensile strength test was used for studying the mechanical properties of the SF fibers. The load cell was set at 50 N. The crosshead speed at 100 mm/min, and the gauge length at 200 mm were used by standard method of Thailand industrial standard of textile test. Five specimens of each SF fiber were measured at the same conditions. As demonstrated in **Table 4.1,** it is found that the highest stress of 0.040 N/mm^2 was obtained of the SF fiber.The stress and strain of the SF fiber were reported in **Table 4.1**. The stresses of the SF fiber were in the range of 0.012 to 0.040 N/mm^2. The strains of the SF fiber ranged from 0.103 to 0.476. The percentage strain of the SF fiber ranged from 10.31 to 47.61%. The average values of 0.024±0.008 N/mm^2, 0.220±0.120 and 22.01±11.99 % were obtained for stress, strain, and percentage strain, respectively.

Table 4.1 The stress and strain of the SF fiber

Samples	Tensile strength		
	Stress (σ) (N/mm^2)	Strain (ε)	Percentage strain (% ε)
1/1*	0.026	0.337	33.39
1/2*	0.026	0.476	47.61
2/1	0.033	0.128	12.84
2/2	0.017	0.175	17.51
3/1	0.040	0.130	12.98
3/2	0.025	0.151	15.08
4/1	0.015	0.156	15.61
4/2	0.022	0.228	22.82
5/1	0.012	0.103	10.31
5/2	0.019	0.319	31.94
Average	0.024±0.008	0.220±0.120	22.01±11.99

In this study, one sample is divided into two tests.

1/1* as sample No.1 of the first test

1/2* as sample No.1 of duplicate test

4.3 Study of PM removal efficiency

4.3.1 Effect of air flow rate

Two sets of experiment were conducted to observe the filtration of PM_{10} and $PM_{2.5}$ using the SF fibers. Initial concentrations of PM_{10} and $PM_{2.5}$ were maintained at about 0.040 ± 0.005 mg/m^3 and 0.020 ± 0.005 mg/m^3, respectively. These concentrations were achieved by controlling the amount of rice bran added into the reactor.

The correlation between average PM_{10} concentration and time at the air flow rate of 3, 4, and 5 L/min is shown in **Fig. 4.11.** As seen from the figure, the initial PM_{10} concentration reached equilibrium at around 4 hrs. Then the treatment of PM_{10} was performed using the different air flow rate of 3, 4, and 5 L/min. The PM_{10} concentration decreased rapidly during the initial period of treatment. PM_{10} concentration decreased from 0.037 mg/m^3 to 0.020 mg/m^3 after the treatment period of 4 hrs. when using the air flow rate of 3 L/min. Also PM_{10} concentration decreased from 0.036 mg/m^3 to 0.018 mg/m^3 and from 0.039 mg/m^3 to 0.011 mg/m^3 when using the air flow rate of 4 L/min and 5 L/min, respectively, after the treatment period of 4 hrs. Then, the PM_{10} concentration tends to reach equilibrium. The results also showed that the PM_{10} removal efficiency increased with the air flow rate as report in **Table 4.2**. This may be due to the higher the air flow rate, the more particles pumped from the reactor to the filter. The highest PM_{10} removal efficiency of 70.39 ± 0.68% was obtained when using the air flow rate of 5 L/min.

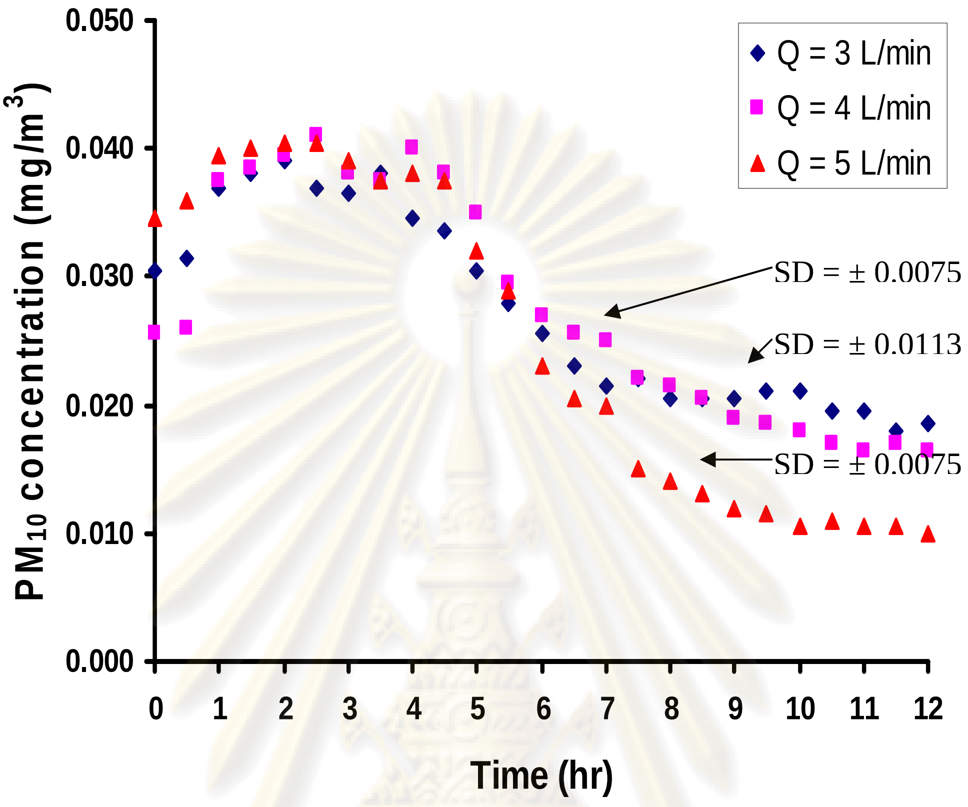


Fig. 4.11 Average PM$_{10}$ concentrations before and after treatment at air flow rate of 3, 4, and 5 L/min (initial concentration of 0.040± 0.005 mg/m^3)

Table 4.2 PM$_{10}$ removal efficiencies of SF fiber at different air flow rates

PM$_{10}$					
Flow rate	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
3 L/min	Test 1	0.0366±0.0092	0.0188±0.0012	48.63	45.24±4.80
	Test 2	0.0363±0.0073	0.0211±0.0044	41.85	
4 L/min	Test 1	0.0360±0.0080	0.0190±0.0034	47.30	51.79±6.35
	Test 2	0.0374±0.0091	0.0163±0.0038	56.28	
5 L/min	Test 1	0.0390±0.0080	0.0114±0.0022	70.87	70.39±0.68
	Test 2	0.0391±0.0018	0.0118±0.0009	69.91	

* Number of data points = 24 points for each period

The correlation between average $PM_{2.5}$ concentration and time at the air flow rate of 3, 4, and 5 L/min is shown in **Fig. 4.12.** As seen from the figure, the initial PM_{10} concentration reached equilibrium at around 4 hrs. Then the treatment of $PM_{2.5}$ was performed using the different air flow rate of 3, 4, and 5 L/min. The $PM_{2.5}$ concentration decreased rapidly during the initial period of treatment. $PM_{2.5}$ concentration decreased from 0.023 mg/m^3 to 0.015 mg/m^3 after the treatment period of 4 hrs. when using the air flow rate of 3 L/min. Also $PM_{2.5}$ concentration decreased from 0.022 mg/m^3 to 0.014 mg/m^3 and from 0.022 mg/m^3 to 0.013 mg/m^3 when using the air flow rate of 4 L/min and 5 L/min, respectively after the treatment period of 3 hrs. Then $PM_{2.5}$ concentration tends to reach equilibrium for all experiments. The results also showed that the $PM_{2.5}$ removal efficiency increased with the air flow rate as reported in **Table 4.3**. The highest $PM_{2.5}$ removal efficiency of 37.85 ± 3.04% was obtained when using the air flow rate of 5 L/min.

Moreover, it can be noted that the PM removal efficiency was base on the air flow rate. Therefore, the PM removal process should be operated with the suitable air flow rate in order to obtain the high PM removal efficiency.

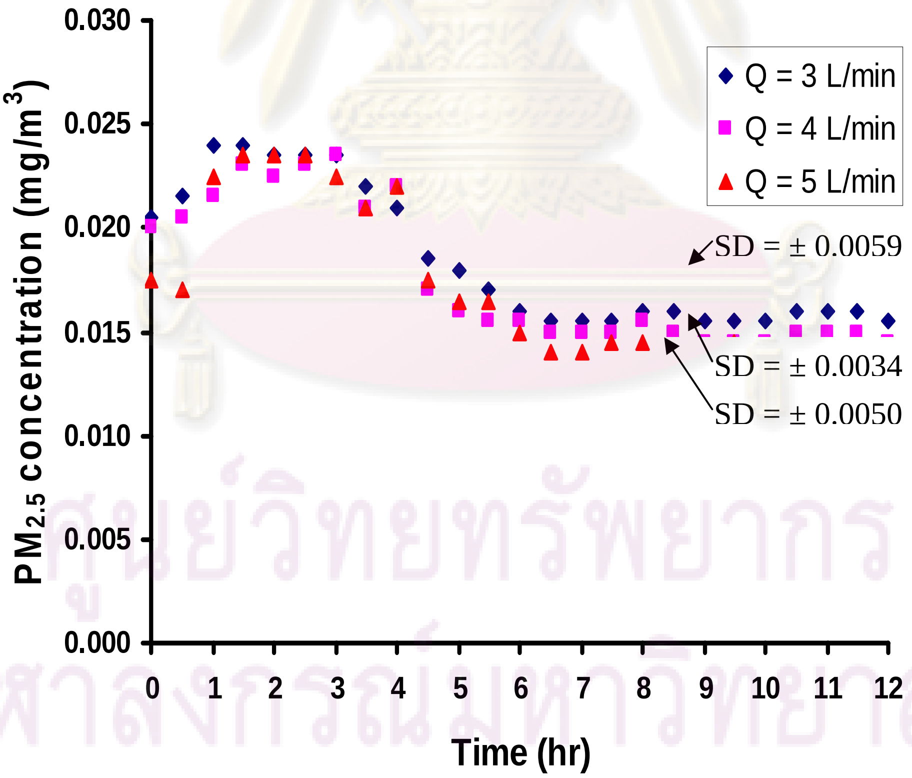


Fig. 4.12 Average $PM_{2.5}$ concentrations before and after treatment at air flow rate of 3, 4, and 5 L/min (initial concentration of 0.020± 0.005 mg/m^3)

Table 4.3 $PM_{2.5}$ removal efficiencies of SF fiber at different air flow rates

$PM_{2.5}$					
Flow rate	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
3 L/min	Test 1	0.0234±0.0045	0.0167±0.0033	28.72	31.63±4.11
	Test 2	0.0222±0.0047	0.0146±0.0029	34.53	
4 L/min	Test 1	0.0212±0.0012	0.0134±0.0027	36.60	36.93±0.47
	Test 2	0.0231±0.0063	0.0145±0.0008	37.26	
5 L/min	Test 1	0.0210±0.0017	0.0126±0.0007	40.00	37.85±3.04
	Test 2	0.0220±0.0028	0.0141±0.0008	35.70	

* Number of data points = 24 points for each period

4.3.2 Effect of initial concentration of PM

The effect of different initial PM_{10} concentrations is shown in **Fig. 4.13**. The initial PM_{10} concentrations of rice bran at original concentration and at 2, 3, 4, and 5 times of the original values were set at approximately 0.040 ± 0.005 mg/m^3, 0.080 ± 0.005 mg/m^3, 0.120 ± 0.005 mg/m^3, 0.160 ± 0.005 mg/m^3 and 0.200 ± 0.005 mg/m^3, respectively. The air flow rate of 5 L/min was applied for all experiments.

As seen from the figure, the PM_{10} concentration decreased rapidly during the initial period of treatment. PM_{10} concentration decreased from 0.039 mg/m^3 to 0.012 mg/m^3 after the treatment period of 4 hrs. when using the initial concentration at 0.040 ± 0.005 mg/m^3 (original value). Also PM_{10} concentration decreased from 0.080 mg/m^3 to 0.041 mg/m^3 after the treatment period of 4 hrs. when using the initial concentration at 2 times of the original value (0.080 ± 0.005 mg/m^3). After the treatment period of 5 hrs., PM_{10} concentration decreased from 0.120 ± 0.005 mg/m^3 to 0.066 mg/m^3 when using the initial concentration at 3 times of the original value (0.120 ± 0.005 mg/m^3), and from 0.160 mg/m^3 to 0.071 mg/m^3 and from 0.200 mg/m^3 to 0.095 mg/m^3 when using the initial concentration at 4 times (0.160 ± 0.005 mg/m^3) and 5 times (0.200 ± 0.005 mg/m^3) of the original values, respectively. Then PM_{10} concentration tends to reach equilibrium for all experiments. The results also showed that the PM_{10} removal efficiency decreased when increasing the initial PM_{10} concentration.

May be in the removal process can not be removal all of concentration that is the high initial concentrations in the reactor and also PM_{10} removal efficiency were decreased. The highest PM_{10} removal efficiency of 70.39±0.68% was obtained when using the initial concentration at 0.040±0.005 mg/m^3. PM_{10} removal efficiencies of the SF fiber at different initial concentrations were reported in **Table 4.4**.

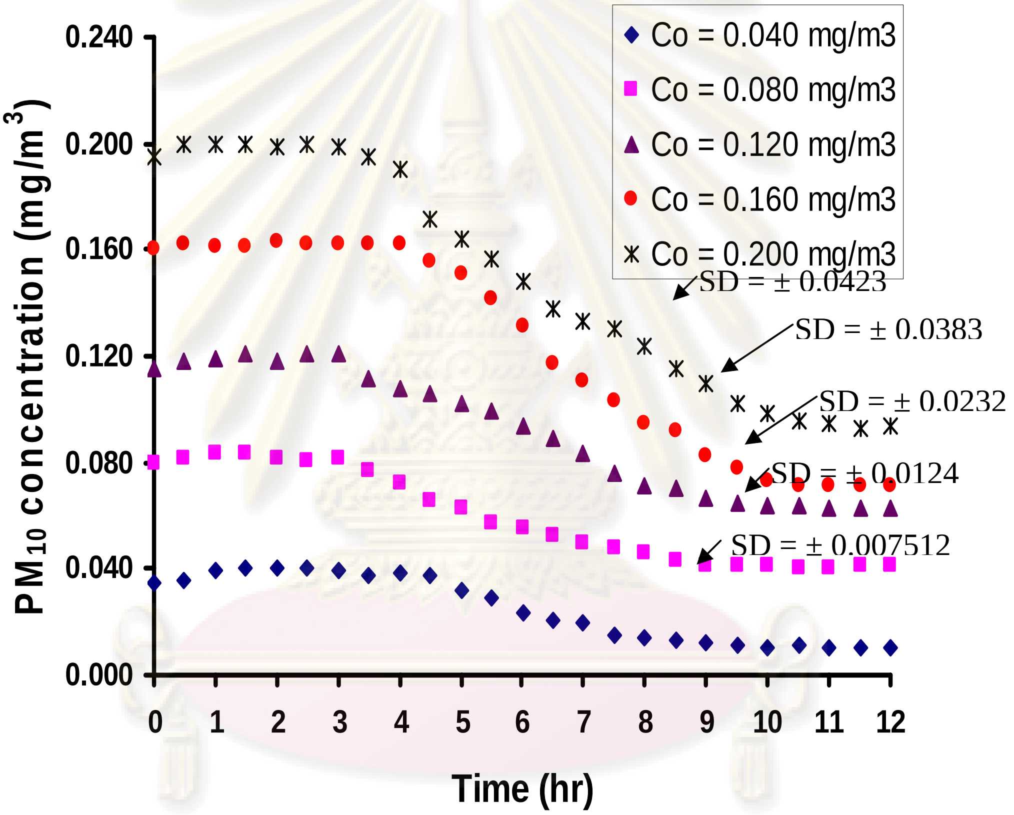


Fig. 4.13 Average PM_{10} concentrations before and after treatment at different initial concentrations and at air flow rate of 5 L/min

Table 4.4 PM$_{10}$ removal efficiencies of SF fiber at different initial concentrations

PM$_{10}$					
Initial concentration	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
original concentration	Test 1	0.0390±0.0080	0.0114±0.0022	70.87	70.39±0.68
	Test 2	0.0391±0.0018	0.0118±0.0009	69.91	
2 times	Test 1	0.0825±0.0029	0.0441±0.0011	46.58	49.10±3.56
	Test 2	0.0801±0.0015	0.0388±0.0030	51.62	
3 times	Test 1	0.1162±0.0024	0.0663±0.0063	42.93	44.49±2.22
	Test 2	0.1214±0.0022	0.0655±0.0024	46.06	
4 times	Test 1	0.1644±0.0013	0.0731±0.0011	55.51	55.38±0.19
	Test 2	0.1582±0.0088	0.0708±0.0011	55.25	
5 times	Test 1	0.1970±0.0016	0.0941±0.0022	52.22	52.41±0.28
	Test 2	0.2012±0.0017	0.0954±0.0017	52.61	

* Number of data points = 24 points for each period

The effect of different initial rice bran concentrations for PM$_{2.5}$ is shown in **Fig. 4.14**. The initial PM$_{10}$ concentrations of rice bran at original concentration and at 2, 3, 4, and 5 times of the original values were set at approximately 0.020 ± 0.005 mg/m^3, 0.040 ± 0.005 mg/m^3, 0.060 ± 0.005 mg/m^3, 0.080 ± 0.005 mg/m^3 and 0.100 ± 0.005 mg/m^3, respectively. The air flow rate of 5 L/min was applied for all experiments.

As seen from the figure, the PM$_{2.5}$ concentration decreased rapidly during the initial period of treatment. PM$_{2.5}$ concentration decreased from 0.022 mg/m^3 to 0.013 mg/m^3 after the treatment period of 4 hrs. when using the initial concentration at 0.020 ± 0.005 mg/m^3. PM$_{2.5}$ concentration decreased from 0.038 mg/m^3 to 0.022 mg/m^3 after the treatment period of 4 hrs. when using the initial concentration at 2 times of the original value (0.040 ± 0.005 mg/m^3). After the treatment period of 5 hrs., PM$_{2.5}$ concentration decreased from 0.0.061 mg/m^3 to 0.030 mg/m^3 when using the initial concentration at 3 times of the original value (0.060 ± 0.005 mg/m^3), from 0.081 mg/m^3 to 0.035 mg/m^3 and from 0.101 mg/m^3 to 0.052 mg/m^3 when using the initial concentration at 4 times (0.080 ± 0.005 mg/m^3) and 5 times (0.100 ± 0.005 mg/m^3) of the original value, respectively. Then PM$_{2.5}$ concentration tends to reach equilibrium for all experiments. The results also showed that the PM$_{2.5}$ removal efficiency increased when increasing the initial concentration. This may be due to removal process of the high initial concentration that fine particles can be rested on the SF fiber. So PM$_{2.5}$ removal efficiencies were increased until over load in initial concentration at 5 times (0.100 ± 0.005 mg/m^3) of the original value. The highest PM$_{2.5}$ removal efficiency of 57.26±3.36% was obtained when using the initial concentration at 0.080 ± 0.005 mg/m^3. PM$_{2.5}$ removal efficiencies of the SF fiber at different initial concentration were reported in **Table 4.5**.

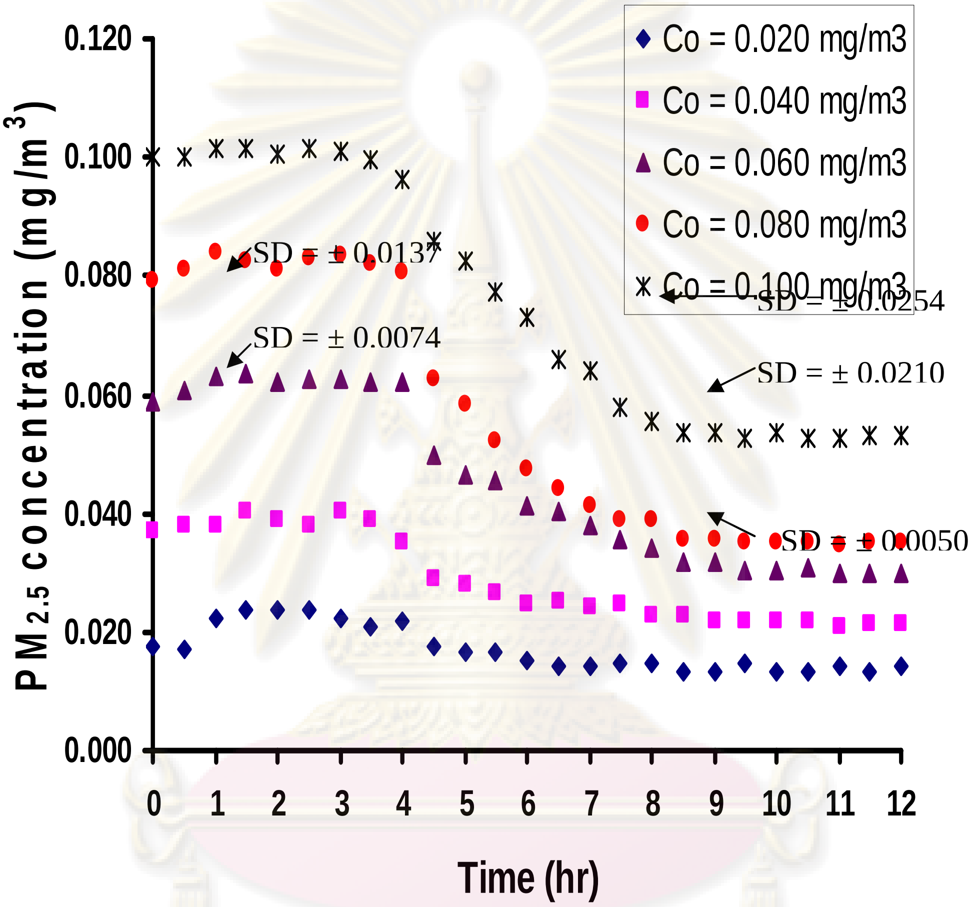


Fig. 4.14 Average PM$_{2.5}$ concentrations before and after treatment at different initial concentrations and at air flow rate of 5 L/min

Table 4.5 $PM_{2.5}$ removal efficiencies of SF fiber at different initial concentrations

$PM_{2.5}$					
Initial concentration	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
Original concentration	Test 1	0.0210±0.0017	0.0126±0.0007	40.00	37.85±3.04
	Test 2	0.0220±0.0028	0.0141±0.0008	35.70	
2 times	Test 1	0.0407±0.0015	0.0248±0.0049	39.10	43.87±6.75
	Test 2	0.0368±0.0018	0.0296±0.0011	48.64	
3 times	Test 1	0.0615±0.0122	0.0321±0.0064	47.79	50.19±3.40
	Test 2	0.0625±0.0012	0.0018±0.5259	52.59	
4 times	Test 1	0.0819±0.0019	0.0370±0.0014	54.88	57.26±3.36
	Test 2	0.0826±0.0162	0.0333±0.0013	59.64	
5 times	Test 1	0.0986±0.0194	0.0512±0.0101	48.07	47.56±0.73
	Test 2	0.1034±0.0016	0.0548±0.0013	47.04	

* Number of data points = 24 points for each period

4.3.3 Effect of filter types

The impact of filter types including the Whatman No.1, the commercial fiber (3M 8210), and the two series SF fibers, for PM_{10} filtration is shown in **Fig. 4.14**. In all experiments, the initial PM_{10} concentrations of rice bran were set approximately 0.040 ± 0.005 mg/m^3. The air flow rate of 5 L/min was applied for all experiments.

As seen from the figure, the PM_{10} concentration decreased rapidly during the initial period of treatment. PM_{10} concentration decreased from 0.041 mg/m^3 to 0.014 mg/m^3 after the treatment period of 5 hrs. when using the Whatman No.1. PM_{10} concentration decreased from 0.043 mg/m^3 to 0.009 mg/m^3 when using the 3M-821, and from 0.043 mg/m^3 to 0.013 mg/m^3 when using the two series SF fibers, after the treatment period of 5 hrs. Then PM_{10} concentration tends to reach equilibrium for all experiments. Results in **Table 4.6** show that the 3M-8210 fiber yielded the highest PM removal efficiency (77.44±1.47%) as compared to other two fibers. However, the 3M-8210 fiber is specifically designed to use as a respiratory protection mask. So fiber of the 3M-8210 must be denser than that of other filters.

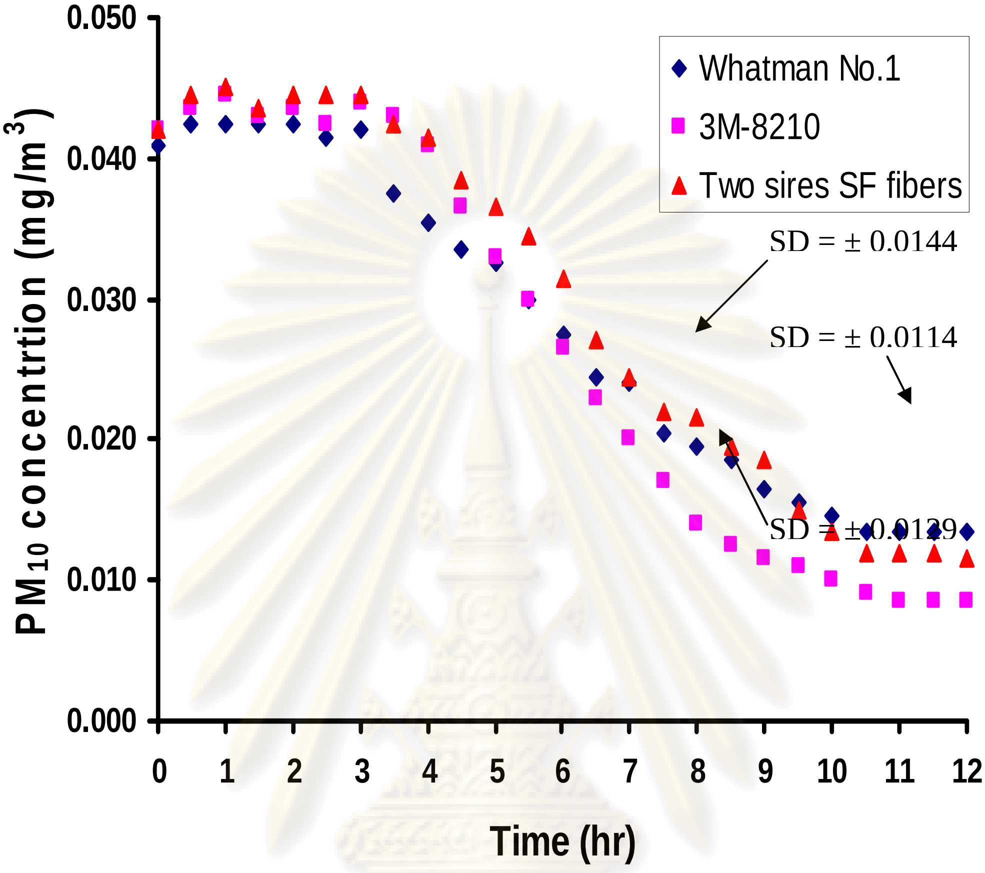


Fig. 4.15 Average PM_{10} concentration before and after treatment when using different types of filter at air flow rate of 5 L/min and initial concentration of 0.040 ± 0.005 mg/m^3.

Table 4.6 PM_{10} removal efficiencies of different filters

PM_{10}					
Types of filter	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
Whatman No.1	Test 1	0.0400±0.0015	0.0149±0.0012	62.45	64.72±3.21
	Test 2	0.0426±0.0015	0.0141±0.0015	66.99	
3M 8210	Test 1	0.0442±0.0012	0.0104±0.0016	76.40	77.44±1.47
	Test 2	0.0429±0.0737	0.0089±0.0013	84.14	
Two series SF fibers	Test 1	0.0429±0.0014	0.0121±0.0017	71.78	69.95±2.60
	Test 2	0.0432±0.0016	0.0138±0.0021	68.11	

* Number of data points = 24 points for each period

The effect of filter types for $PM_{2.5}$ filtration is also included in this study. In all experiments, the initial $PM_{2.5}$ concentrations of rice bran were set at approximately 0.020 ± 0.005 mg/m^3. The air flow rate of 5 L/min was applied for all experiments.

As seen from Fig. 4.16, the $PM_{2.5}$ concentration decreased rapidly during the initial period of treatment. $PM_{2.5}$ concentration decreased from 0.023 mg/m^3 to 0.011 mg/m^3 after the treatment period of 6 hrs. when using the Whatman No.1. Also $PM_{2.5}$ concentration decreased from 0.022 mg/m^3 to 0.008 mg/m^3 when using the 3M-8210 and from 0.022 mg/m^3 to 0.009 mg/m^3 when using the two series SF fibers. after the treatment period of 6 hrs. Then $PM_{2.5}$ concentration tends to reach equilibrium for all experiments. The highest $PM_{2.5}$ removal efficiency of 63.50±7.91% was obtained when using the 3M-8210 fiber. $PM_{2.5}$ removal efficiencies of the three filters were reported in **Table 4.7**.

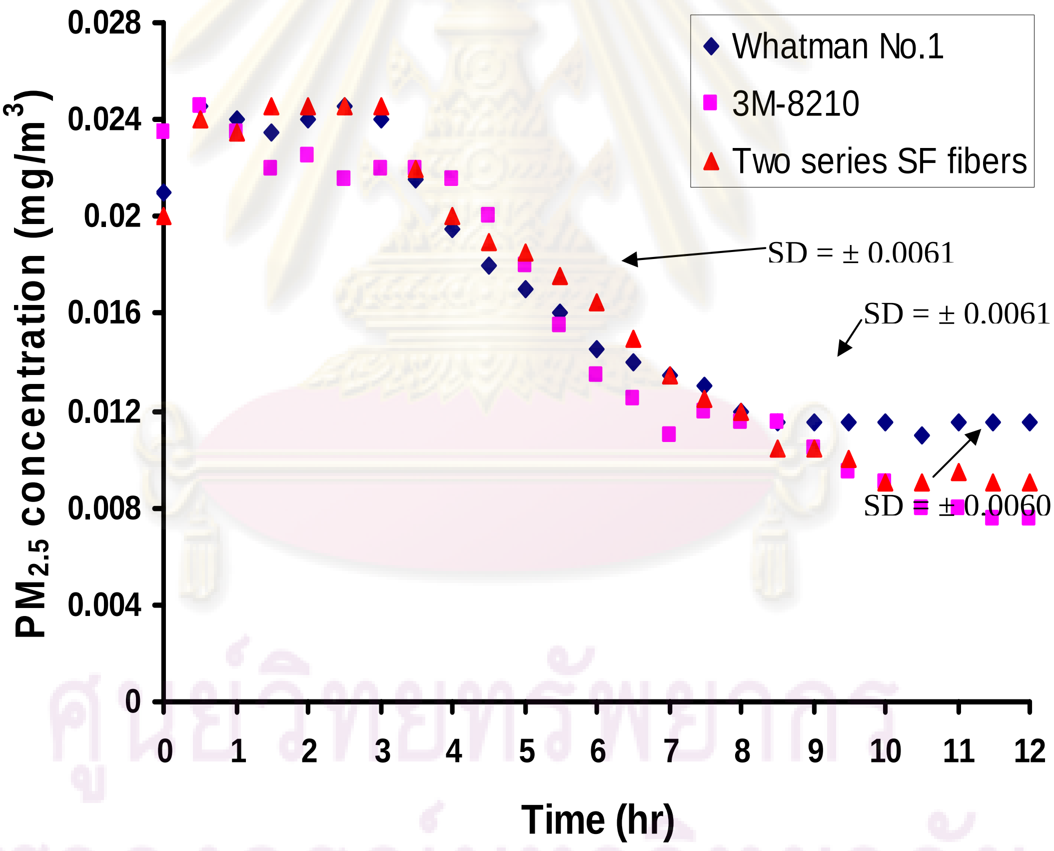


Fig. 4.16 Average $PM_{2.5}$ concentration before and after treatment when using different types of filter at air flow rate of 5 L/min and initial concentration of 0.020 ± 0.005 mg/m^3.

Table 4.7 $PM_{2.5}$ removal efficiencies of different filters

$PM_{2.5}$					
Types of filter	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
Whatman No.1	Test 1	0.0234±0.0009	0.0108±0.0005	53.77	52.16±2.27
	Test 2	0.0235±0.0014	0.0116±0.0032	50.56	
3M 8210	Test 1	0.0228±0.0012	0.0071±0.0012	69.09	63.50±7.91
	Test 2	0.0221±0.0043	0.0093±0.0008	57.91	
Two series SF fibers	Test 1	0.0236±0.0014	0.0093±0.0007	60.46	59.42±1.47
	Test 2	0.0228±0.0013	0.0095±0.0010	58.38	

* Number of data points = 24 points for each period

4.3.4 Cost comparison between the SF fiber and the commercial fiber (3M 8210)

Cost comparison between two types of fiber is shown in **Table 4.8**. The results show that the SF fiber has much less cost than the 3M-8210 fiber. Total cost for synthesis the SF fiber is approximately 0.61 baht/piece, while cost of commercial fiber is 6.50 baht/piece.

Table 4.8 Cost comparison of fibers

Types of fiber	Price (Baht/Piece ^{a})
SF fiber ^{b}	0.61
Commercial fiber(3M-8210) ^{c}	6.50

[a] Diameter of each piece is 5.5 cm
[b] Total cost for synthesis SF fiber per piece
[c] Commercial fiber of mask respiratory protection (3M-8210)

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this work, the study of synthesis and PM removal efficiency of the SF fiber can be concluded that:

5.1 The SF fiber was readily synthesized using the Na_2CO_3 solution. It was de-gummed in alkaline solution at 90 ºC for 60 mins, washed with distilled water, and dried at 80 ºC for 3 hrs in a vacuum oven.

5.2 The physical characteristics of SF fiber were examined by SEM analysis. The SEM micrographs of SF fiber before PM filtration revealed the fibrous morphology of the SF fiber. An average diameter of the SF fiber was estimated to be approximately 10 µm. The SEM images of SF fibers after PM filtration revealed the deposition of fine particle on the fiber.

5.3 The physical properties were measured by BJH method. The pore size of the SF fiber was estimated to be 24.664 ± 0.005 Å and was classified as mesopore.

5.4 The mechanical properties of the SF fibers were investigated. The average stress was obtained of 0.024±0.008 N/mm^2. The strain and percentage strain of 0.220±0.120 and 22.01±11.99 % were obtained, respectively.

5.5 The effect of air flow rate of aerosol personal pump was investigated at 3, 4, and 5 L/min. The PM removal efficiency of the SF fiber increased with an increasing of air flow rate. The highest removal efficiencies of 70.39 ± 0.68 % and 37.85 ± 3.04 % were obtained for PM_{10} and $PM_{2.5}$, respectively when using 5 L/min of air flow rate.

5.6 The initial PM concentration was varied to original concentration and at 2, 3, 4, and 5 times of the original values. The highest PM_{10} removal efficiency of 70.39 ± 0.68 % was obtained when using the initial concentration of 0.040 ± 0.005 mg/m^3, also for the highest $PM_{2.5}$ removal efficiency of 57.26±3.36% was obtained when using the initial concentration of 0.080 ± 0.005 mg/m^3.

5.7 The effect of the filter types for filtration of Whatman No.1, the commercial fiber (3M 8210), and two series SF fibers were studied. The 3M-8210 fiber has the highest PM removal efficiency both PM_{10} and $PM_{2.5}$. PM removal efficiency of 77.44 ± 1.47 % and 63.50 ± 7.91 % were obtained when using the 3M-8210 fiber for PM_{10} and $PM_{2.5}$ respectively.

5.8 Cost comparison between two types of fiber was compared. The results show that the SF fiber has much less cost than the 3M-8210 fiber. Total cost for synthesis the SF fiber is approximately 0.61 baht/piece, while cost of commercial fiber is 6.50 baht/piece.

The results obtained form this study may be useful for developing with preparation of the SF fiber. Consequently, the SF fiber may be used as an alternative material for removing particulate matter in air and also it has less cost for synthesis.

5.2 Recommendations

In the future work, the step of preparation of the SF fiber should be controlled thickness and dense of the SF fiber. Moreover, the different ranges of air flow rate should be studied in order to provide a better understanding of the PM removal. Finally, in the future work should be carefully pressure drop during period of treatment.

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APPENDICES

APPENDIX A

Fig. A1 Respiratory protection (Commercial fiber 3M-8210)

Fig. A Respiratory protection (Commercial fiber 3M-8210)
after cut in diameter of 33 mm

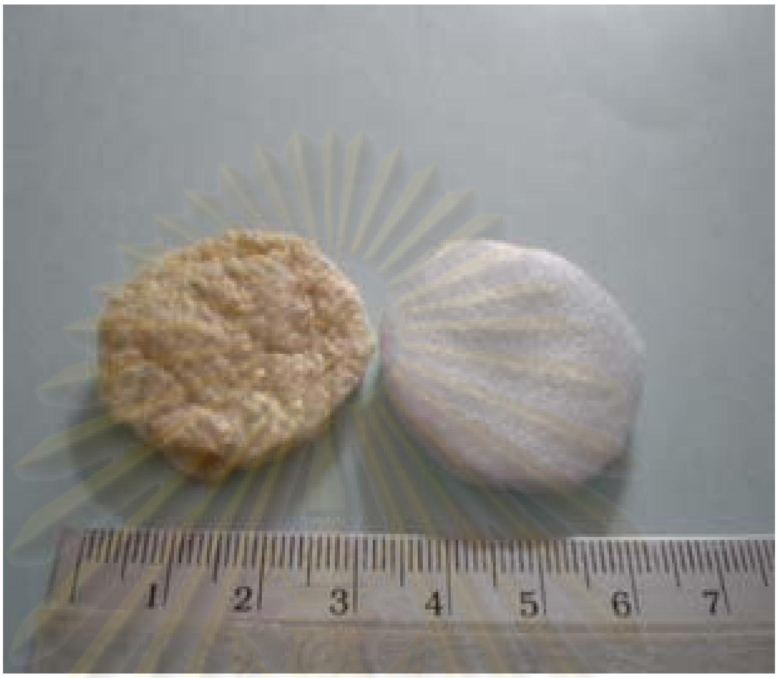


Fig. A3 Comparison of the SF fiber and respiratory protection (Commercial fiber 3M-8210)

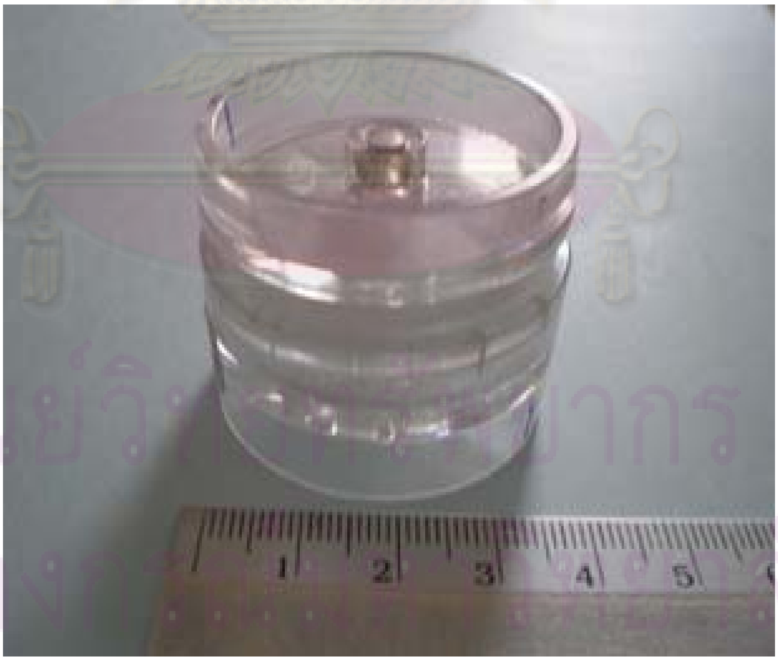


Fig. A4 Respiratory protection (Commercial fiber 3M-8210) placed inside filter holder

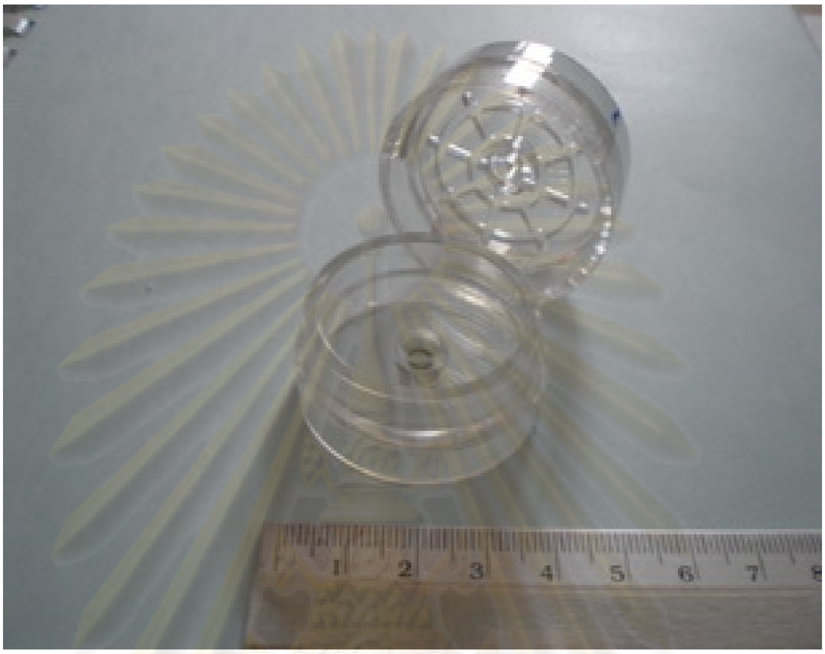
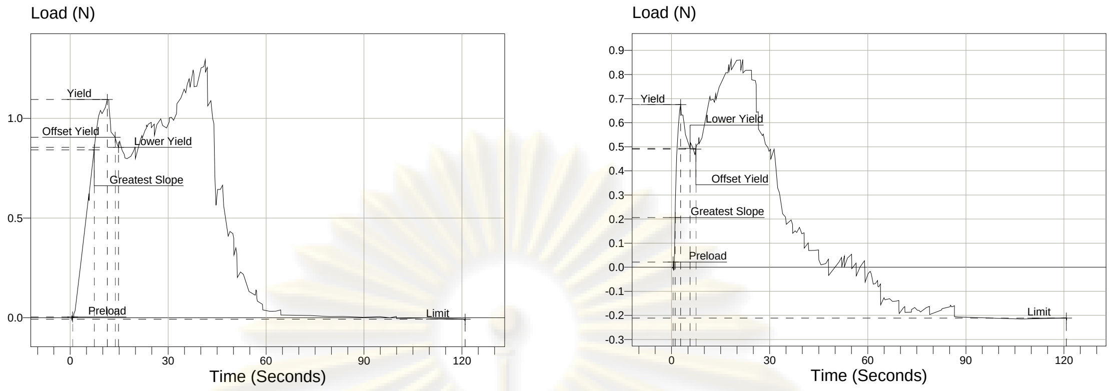
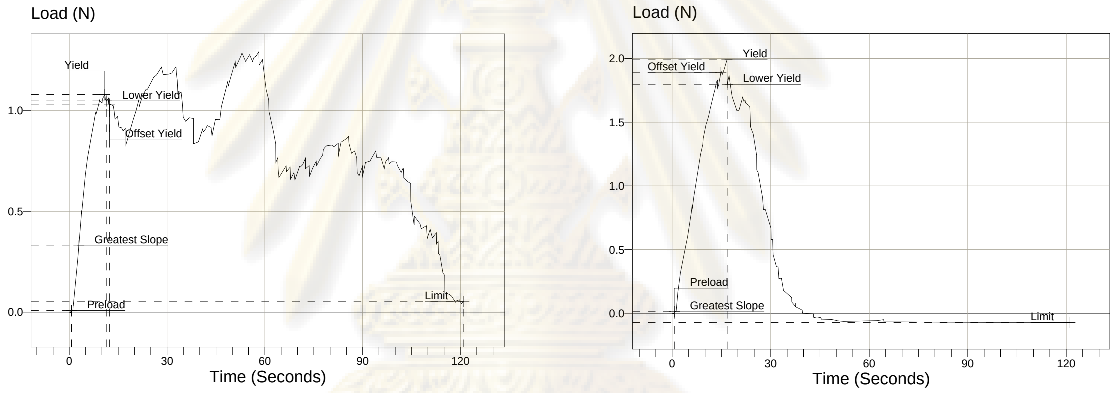


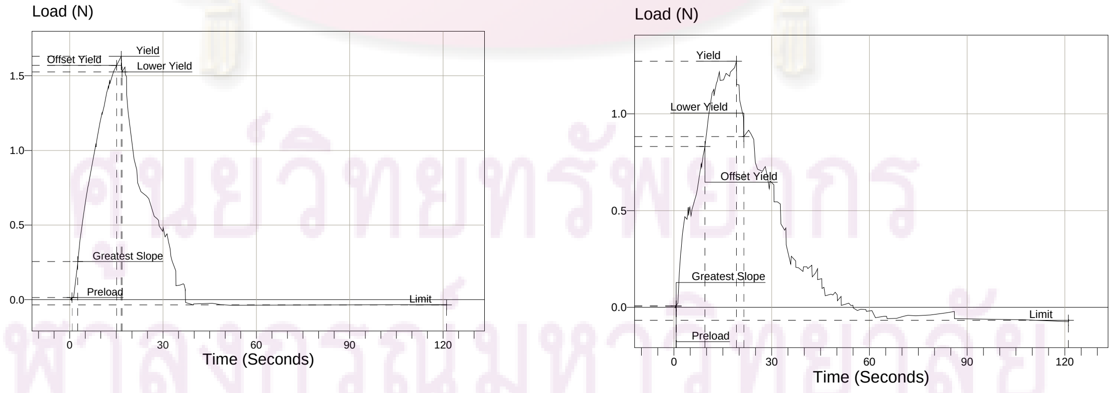
Fig. A5 Filter holder



Sample 1/1 Sample 2/2

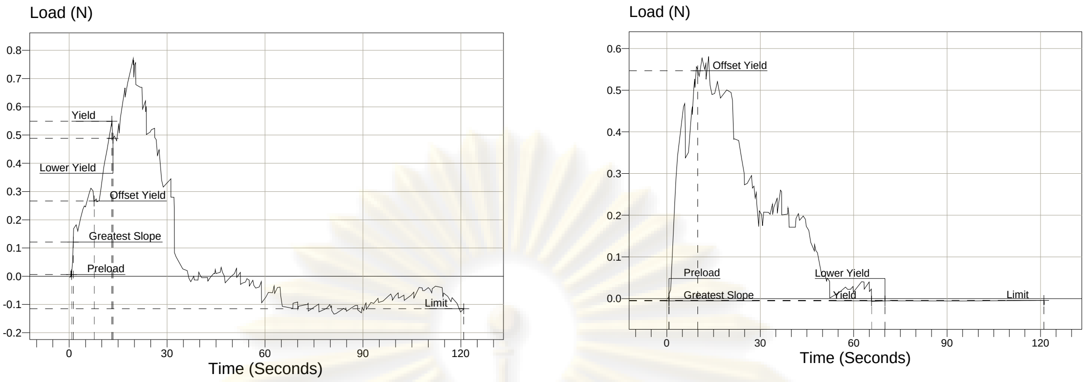


Sample 1/2 Sample 3/1



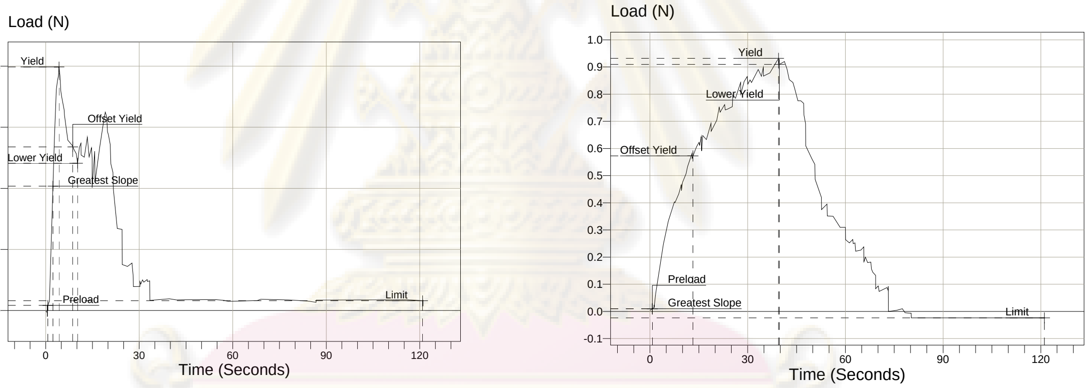
Sample 2/1 Sample 3/2

Fig. A6 Tensile strength of the SF fiber by controlling load cell at 50 N, the crosshead speed at 100 mm/min, and the gauge length at 200 mm



Sample 4/1

Sample 5/1



Sample 4/2

Sample 5/2

Fig. A6 Tensile strength of the SF fiber by controlling load cell at 50 N, the crosshead speed at 100 mm/min, and the gauge length at 200 mm

APPENDIX B

Table B1 The stress and strain of the SF fiber

Samples	Gauge length (mm)	Speed (mm/min)	Maximum load (N)	Deflection at maximum load (mm)	Percentage strain (%)
1/1*	200	100	0.493	48.533	24.266
1/2*	200	100	1.082	45.645	22.822
2/1	200	100	1.631	25.686	12.843
2/2	200	100	0.862	35.023	17.512
3/1	200	100	1.990	25.957	12.979
3/2	200	100	1.273	30.161	15.081
4/1	200	100	0.771	31.213	15.607
4/2	200	100	1.291	95.216	47.608
5/1	200	100	0.581	20.616	10.308
5/2	200	100	0.932	63.888	31.944

In this study, one sample is devised in to two tests.
1/1* as sample No.1 of the first test
1/2* as sample No.1 of duplicate test

Table B2 BJH analysis of the SF fiber

Samples	Physical properties		
	Specific surface area (m^2/g)	Specific pore volume (cc/g)	Pore size (Å)
1/1*	67.380	0.036	24.660
1/2*	57.270	0.031	24.670
2/1	53.760	0.029	24.670
2/2	44.040	0.024	24.660
3/1	50.540	0.027	24.670
3/2	59.260	0.032	24.660
4/1	74.380	0.040	24.660
4/2	76.680	0.041	24.660
5/1	60.490	0.032	24.660
5/2	103.400	0.072	24.670
Average	64.720 ± 16.969	0.036 ± 0.014	24.664 ± 0.005

In this study, one sample is devised in to two tests.

1/1* as sample No.1 of the first test
1/2* as sample No.1 of duplicate test

Table B3 Accumulative mass flux of $PM_{2.5}$ on filter media

Time(hr)	$PM_{2.5}$			
	Accumulative mass flux (mg/hr-m^2)			
	SF flow rate (3L/min)	SF flow rate (4L/min)	SF flow rate (5L/min)	3M8210 flow rate (5L/min)
0	Avg. initial mass flux = 4.73	Avg. initial mass flux = 6.14	Avg. initial mass flux = 7.64	Avg. initial mass flux= 7.92
5	0.95	1.51	1.86	1.61
6	1.37	1.80	2.38	3.19
7	1.37	1.80	2.56	3.72
8	1.37	1.80	2.73	3.89
9	1.47	1.94	2.91	4.24
10	1.47	1.94	2.91	4.77
11	1.47	1.94	2.91	5.29
12	1.58	2.08	3.09	5.29

Table B4 Accumulative mass flux of PM_{10} on filter media

Time(hr)	PM_{10}			
	Accumulative mass flux (mg/hr-m^2)			
	SF flow rate (3L/min)	SF flow rate (4L/min)	SF flow rate (5L/min)	3M8210 flow rate (5L/min)
0	Avg. initial mass flux = 7.47	Avg. initial mass flux = 10.10	Avg. initial mass flux = 13.40	Avg. initial mass flux= 15.10
5	1.05	0.31	2.21	3.51
6	2.10	2.55	5.36	5.79
7	2.95	3.11	6.42	8.06
8	3.16	4.10	8.52	10.20
9	3.16	4.80	9.22	11.10
10	3.05	5.08	9.75	11.60
11	3.37	5.50	9.75	11.90
12	3.58	5.50	9.92	12.10

Table B5 Study effect of air flow rate of aerosol personal pump at 3 L/min

$PM_{2.5}$							
Air flow rate 3 L/min							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.022	0.019	0.0205	6.1	0.017	0.015	0.0160
0.1	0.022	0.019	0.0205	6.2	0.018	0.016	0.0170
0.2	0.023	0.020	0.0215	6.3	0.018	0.015	0.0165
0.3	0.023	0.020	0.0215	6.4	0.017	0.015	0.0160
0.4	0.022	0.021	0.0215	6.5	0.016	0.016	0.0160
0.5	0.024	0.022	0.0230	7.0	0.016	0.015	0.0155
1.0	0.024	0.024	0.0240	7.1	0.016	0.015	0.0155
1.1	0.025	0.023	0.0240	7.2	0.017	0.014	0.0155
1.2	0.024	0.024	0.0240	7.3	0.016	0.014	0.0150
1.3	0.024	0.024	0.0240	7.4	0.016	0.015	0.0155
1.4	0.023	0.024	0.0235	7.5	0.017	0.014	0.0155
1.5	0.024	0.023	0.0235	8.0	0.017	0.015	0.0160
2.0	0.024	0.023	0.0235	8.1	0.016	0.014	0.0150
2.1	0.023	0.024	0.0235	8.2	0.016	0.015	0.0155
2.2	0.024	0.024	0.0240	8.3	0.017	0.015	0.0160
2.3	0.024	0.023	0.0235	8.4	0.017	0.014	0.0155
2.4	0.025	0.024	0.0245	8.5	0.016	0.015	0.0155
2.5	0.024	0.023	0.0235	9.0	0.017	0.014	0.0155
3.0	0.024	0.023	0.0235	9.1	0.017	0.015	0.0160
3.1	0.024	0.023	0.0235	9.2	0.017	0.015	0.0160
3.2	0.023	0.022	0.0225	9.3	0.017	0.014	0.0155
3.3	0.022	0.022	0.0220	9.4	0.017	0.014	0.0155
3.4	0.023	0.023	0.0230	9.5	0.016	0.014	0.0150
3.5	0.023	0.020	0.0215	10.0	0.017	0.014	0.0155
4.0	0.022	0.019	0.0205	10.1	0.016	0.015	0.0155
4.1	0.020	0.019	0.0195	10.2	0.017	0.014	0.0155
4.2	0.020	0.02	0.0200	10.3	0.017	0.015	0.0160
4.3	0.019	0.018	0.0185	10.4	0.017	0.015	0.0160
4.4	0.019	0.019	0.0190	10.5	0.016	0.015	0.0155
4.5	0.020	0.020	0.0200	11.0	0.017	0.015	0.0160
5.0	0.018	0.018	0.0180	11.1	0.017	0.015	0.0160
5.1	0.016	0.019	0.0175	11.2	0.016	0.014	0.0150
5.2	0.018	0.018	0.0180	11.3	0.017	0.015	0.0160
5.3	0.017	0.017	0.0170	11.4	0.017	0.014	0.0155
5.4	0.018	0.018	0.0180	11.5	0.016	0.015	0.0155
5.5	0.017	0.016	0.0165	12.0	0.017	0.014	0.0155
6.0	0.017	0.015	0.0160				

Table B6 Study effect of air flow rate of aerosol personal pump at 4 L/min

$PM_{2.5}$							
Air flow rate 4 L/min							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.019	0.021	0.0200	6.1	0.019	0.018	0.0185
0.1	0.019	0.020	0.0195	6.2	0.018	0.017	0.0175
0.2	0.020	0.021	0.0205	6.3	0.016	0.018	0.0170
0.3	0.019	0.022	0.0205	6.4	0.017	0.017	0.0170
0.4	0.021	0.021	0.0210	6.5	0.018	0.017	0.0175
0.5	0.021	0.022	0.0215	7.0	0.019	0.016	0.0175
1.0	0.020	0.023	0.0215	7.1	0.018	0.016	0.0170
1.1	0.021	0.022	0.0215	7.2	0.018	0.016	0.0170
1.2	0.022	0.023	0.0225	7.3	0.017	0.015	0.0160
1.3	0.022	0.024	0.0230	7.4	0.016	0.016	0.0160
1.4	0.021	0.023	0.0220	7.5	0.016	0.015	0.0155
1.5	0.022	0.024	0.0230	8.0	0.016	0.016	0.0160
2.0	0.021	0.024	0.0225	8.1	0.015	0.015	0.0150
2.1	0.021	0.025	0.0230	8.2	0.014	0.015	0.0145
2.2	0.023	0.024	0.0235	8.3	0.014	0.016	0.0150
2.3	0.022	0.024	0.0230	8.4	0.013	0.015	0.0140
2.4	0.022	0.025	0.0235	8.5	0.014	0.015	0.0145
2.5	0.023	0.025	0.0240	9.0	0.014	0.015	0.0145
3.0	0.023	0.024	0.0235	9.1	0.013	0.014	0.0135
3.1	0.023	0.025	0.0240	9.2	0.013	0.015	0.0140
3.2	0.021	0.024	0.0225	9.3	0.013	0.014	0.0135
3.3	0.020	0.023	0.0215	9.4	0.014	0.014	0.0140
3.4	0.021	0.022	0.0215	9.5	0.013	0.015	0.0140
3.5	0.022	0.023	0.0225	10.0	0.013	0.014	0.0135
4.0	0.021	0.023	0.0220	10.1	0.013	0.015	0.0140
4.1	0.020	0.022	0.0210	10.2	0.013	0.015	0.0140
4.2	0.019	0.023	0.0210	10.3	0.013	0.014	0.0135
4.3	0.019	0.022	0.0205	10.4	0.013	0.015	0.0140
4.4	0.018	0.021	0.0195	10.5	0.013	0.014	0.0135
4.5	0.019	0.021	0.0200	11.0	0.013	0.013	0.0130
5.0	0.019	0.020	0.0195	11.1	0.013	0.014	0.0135
5.1	0.018	0.020	0.0190	11.2	0.013	0.013	0.0130
5.2	0.018	0.019	0.0185	11.3	0.014	0.015	0.0145
5.3	0.019	0.019	0.0190	11.4	0.013	0.014	0.0135
5.4	0.018	0.018	0.0180	11.5	0.013	0.013	0.0130
5.5	0.018	0.017	0.0175	12.0	0.013	0.014	0.0135
6.0	0.019	0.017	0.0180				

Table B7 Study effect of air flow rate of aerosol personal pump at 5 L/min

PM$_{2.5}$							
Air flow rate 5 L/min							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.019	0.016	0.0175	6.1	0.014	0.014	0.0140
0.1	0.018	0.017	0.0175	6.2	0.014	0.015	0.0145
0.2	0.019	0.018	0.1850	6.3	0.014	0.014	0.0140
0.3	0.019	0.015	0.0170	6.4	0.013	0.014	0.0135
0.4	0.017	0.020	0.0185	6.5	0.014	0.015	0.0145
0.5	0.021	0.021	0.0210	7.0	0.014	0.015	0.0145
1.0	0.022	0.023	0.0225	7.1	0.014	0.014	0.0140
1.1	0.021	0.024	0.0225	7.2	0.013	0.015	0.0140
1.2	0.020	0.023	0.0215	7.3	0.014	0.015	0.0145
1.3	0.022	0.025	0.0235	7.4	0.013	0.013	0.0130
1.4	0.022	0.025	0.0235	7.5	0.013	0.014	0.0135
1.5	0.022	0.024	0.0230	8.0	0.013	0.016	0.0145
2.0	0.022	0.025	0.0235	8.1	0.012	0.015	0.0135
2.1	0.023	0.024	0.0235	8.2	0.013	0.015	0.0140
2.2	0.024	0.022	0.0230	8.3	0.012	0.015	0.0135
2.3	0.023	0.024	0.0235	8.4	0.012	0.015	0.0135
2.4	0.023	0.025	0.024	8.5	0.013	0.014	0.0135
2.5	0.021	0.022	0.0215	9.0	0.013	0.014	0.0135
3.0	0.022	0.023	0.0225	9.1	0.014	0.014	0.0140
3.1	0.021	0.022	0.0215	9.2	0.012	0.014	0.0130
3.2	0.021	0.021	0.0210	9.3	0.014	0.014	0.0140
3.3	0.020	0.022	0.0210	9.4	0.013	0.014	0.0135
3.4	0.020	0.022	0.0210	9.5	0.013	0.013	0.0130
3.5	0.022	0.023	0.0225	10.0	0.012	0.015	0.0135
4.0	0.021	0.023	0.0220	10.1	0.012	0.014	0.0130
4.1	0.020	0.020	0.0200	10.2	0.012	0.015	0.0135
4.2	0.019	0.019	0.0190	10.3	0.012	0.015	0.0135
4.3	0.018	0.017	0.0175	10.4	0.013	0.014	0.0135
4.4	0.018	0.018	0.0180	10.5	0.012	0.013	0.0125
4.5	0.017	0.017	0.0170	11.0	0.013	0.014	0.0135
5.0	0.016	0.017	0.0165	11.1	0.012	0.014	0.013
5.1	0.018	0.016	0.0170	11.2	0.012	0.013	0.0125
5.2	0.016	0.017	0.0165	11.3	0.012	0.013	0.0125
5.3	0.017	0.016	0.0165	11.4	0.013	0.014	0.0135
5.4	0.016	0.015	0.0155	11.5	0.013	0.013	0.0130
5.5	0.015	0.016	0.0155	12.0	0.013	0.013	0.0130
6.0	0.015	0.015	0.0150				

Table B8 Study effect of air flow rate of aerosol personal pump at 3, 4, and 5 L/min

$PM_{2.5}$					
Flow rate	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
3 L/min	Test 1	0.0234±0.0045	0.0167±0.0033	28.72	31.63±4.11
	Test 2	0.0222±0.0047	0.0146±0.0029	34.53	
4 L/min	Test 1	0.0212±0.0012	0.0134±0.0027	36.60	36.93±0.47
	Test 2	0.0231±0.0063	0.0145±0.0008	37.26	
5 L/min	Test 1	0.0210±0.0017	0.0126±0.0007	40.00	37.85±3.04
	Test 2	0.0220±0.0028	0.0141±0.0008	35.70	

* Number of data points = 24 points for each period

Table B9 Study effect of air flow rate of aerosol personal pump at 3 L/min

PM_{10}							
Air flow rate 3 L/min							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.023	0.038	0.0305	6.1	0.028	0.024	0.0260
0.1	0.024	0.037	0.0305	6.2	0.026	0.022	0.0240
0.2	0.025	0.039	0.0320	6.3	0.025	0.021	0.0230
0.3	0.028	0.039	0.0335	6.4	0.024	0.025	0.0245
0.4	0.029	0.041	0.0350	6.5	0.022	0.024	0.0230
0.5	0.038	0.038	0.0380	7.0	0.022	0.021	0.0215
1.0	0.039	0.035	0.0370	7.1	0.023	0.022	0.0225
1.1	0.036	0.036	0.0360	7.2	0.020	0.024	0.0220
1.2	0.035	0.035	0.0350	7.3	0.021	0.023	0.0220
1.3	0.041	0.035	0.0380	7.4	0.022	0.022	0.0220
1.4	0.040	0.039	0.0395	7.5	0.020	0.021	0.0205
1.5	0.041	0.036	0.0385	8.0	0.020	0.021	0.0205
2.0	0.043	0.035	0.0390	8.1	0.021	0.022	0.0215
2.1	0.040	0.035	0.0375	8.2	0.018	0.021	0.0195
2.2	0.040	0.037	0.0385	8.3	0.019	0.022	0.0205
2.3	0.038	0.036	0.0370	8.4	0.02	0.024	0.0220
2.4	0.041	0.037	0.0390	8.5	0.019	0.022	0.0205
2.5	0.039	0.035	0.0370	9.0	0.018	0.023	0.0205
3.0	0.038	0.035	0.0365	9.1	0.018	0.021	0.0195
3.1	0.041	0.036	0.0385	9.2	0.019	0.022	0.0205
3.2	0.041	0.035	0.0380	9.3	0.020	0.023	0.0215
3.3	0.040	0.036	0.0380	9.4	0.018	0.021	0.0195
3.4	0.041	0.034	0.0375	9.5	0.020	0.230	0.1250
3.5	0.039	0.035	0.0370	10.0	0.020	0.022	0.0210
4.0	0.035	0.034	0.0345	10.1	0.021	0.021	0.0210
4.1	0.035	0.032	0.0335	10.2	0.02	0.020	0.0200
4.2	0.036	0.034	0.0350	10.3	0.019	0.020	0.0195
4.3	0.034	0.033	0.0335	10.4	0.018	0.022	0.0200
4.4	0.035	0.030	0.0325	10.5	0.018	0.023	0.0205
4.5	0.032	0.031	0.0315	11.0	0.018	0.021	0.0195
5.0	0.031	0.030	0.0305	11.1	0.019	0.020	0.0195
5.1	0.032	0.031	0.0315	11.2	0.017	0.020	0.0185
5.2	0.030	0.030	0.0300	11.3	0.017	0.019	0.0180
5.3	0.028	0.028	0.0280	11.4	0.018	0.018	0.0180
5.4	0.029	0.029	0.0290	11.5	0.017	0.018	0.0175
5.5	0.026	0.025	0.0255	12.0	0.018	0.019	0.0185
6.0	0.027	0.024	0.0255				

Table B10 Study effect of air flow rate of aerosol personal pump at 4 L/min

PM$_{10}$							
Air flow rate 4 L/min							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.027	0.024	0.0255	6.1	0.026	0.027	0.0265
0.1	0.029	0.029	0.0290	6.2	0.025	0.028	0.0265
0.2	0.032	0.030	0.0310	6.3	0.025	0.026	0.0255
0.3	0.027	0.025	0.0260	6.4	0.027	0.025	0.0260
0.4	0.029	0.029	0.0290	6.5	0.025	0.024	0.0245
0.5	0.038	0.034	0.0360	7.0	0.026	0.024	0.0250
1.0	0.035	0.040	0.0375	7.1	0.026	0.023	0.0245
1.1	0.039	0.039	0.0390	7.2	0.025	0.021	0.0230
1.2	0.039	0.038	0.0385	7.3	0.024	0.020	0.0220
1.3	0.038	0.039	0.0385	7.4	0.024	0.020	0.0220
1.4	0.038	0.039	0.0385	7.5	0.023	0.020	0.0215
1.5	0.039	0.040	0.0395	8.0	0.022	0.021	0.0215
2.0	0.038	0.041	0.0395	8.1	0.023	0.020	0.0215
2.1	0.038	0.040	0.0390	8.2	0.022	0.019	0.0205
2.2	0.039	0.042	0.0405	8.3	0.021	0.020	0.0205
2.3	0.039	0.043	0.0410	8.4	0.020	0.020	0.0200
2.4	0.037	0.041	0.0390	8.5	0.021	0.019	0.0200
2.5	0.039	0.040	0.0395	9.0	0.020	0.018	0.0190
3.0	0.038	0.038	0.0380	9.1	0.021	0.018	0.0195
3.1	0.038	0.039	0.0385	9.2	0.020	0.017	0.0185
3.2	0.037	0.040	0.0385	9.3	0.020	0.017	0.0185
3.3	0.035	0.040	0.0375	9.4	0.019	0.016	0.0175
3.4	0.036	0.041	0.0385	9.5	0.020	0.018	0.0190
3.5	0.037	0.041	0.0390	10.0	0.019	0.017	0.0180
4.0	0.038	0.042	0.0400	10.1	0.018	0.017	0.0175
4.1	0.037	0.040	0.0385	10.2	0.019	0.016	0.0175
4.2	0.038	0.040	0.0390	10.3	0.018	0.016	0.0170
4.3	0.036	0.040	0.0380	10.4	0.018	0.015	0.0165
4.4	0.038	0.038	0.0380	10.5	0.017	0.016	0.0165
4.5	0.036	0.035	0.0355	11.0	0.018	0.015	0.0165
5.0	0.036	0.032	0.0340	11.1	0.018	0.015	0.0165
5.1	0.035	0.031	0.0330	11.2	0.018	0.014	0.0160
5.2	0.032	0.032	0.0320	11.3	0.019	0.015	0.0170
5.3	0.029	0.030	0.0295	11.4	0.019	0.014	0.0165
5.4	0.030	0.030	0.0300	11.5	0.018	0.015	0.0165
5.5	0.038	0.028	0.0330	12.0	0.018	0.015	0.0165
6.0	0.027	0.027	0.0270				

Table B11 Study effect of air flow rate of aerosol personal pump at 5 L/min

PM_{10}							
Air flow rate 5 L/min							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.034	0.035	0.0345	6.1	0.025	0.022	0.0235
0.1	0.036	0.036	0.0360	6.2	0.025	0.022	0.0235
0.2	0.035	0.039	0.0370	6.3	0.020	0.021	0.0205
0.3	0.034	0.038	0.0360	6.4	0.021	0.021	0.0210
0.4	0.039	0.040	0.0395	6.5	0.020	0.021	0.0205
0.5	0.038	0.042	0.0400	7.0	0.020	0.020	0.0200
1.0	0.038	0.041	0.0395	7.1	0.020	0.018	0.0190
1.1	0.039	0.040	0.0395	7.2	0.018	0.015	0.0165
1.2	0.040	0.041	0.0405	7.3	0.018	0.012	0.0150
1.3	0.038	0.042	0.0400	7.4	0.018	0.014	0.0160
1.4	0.041	0.040	0.0405	7.5	0.016	0.015	0.0155
1.5	0.040	0.040	0.0400	8.0	0.015	0.013	0.014
2.0	0.040	0.041	0.0405	8.1	0.016	0.013	0.0145
2.1	0.041	0.039	0.0400	8.2	0.015	0.012	0.0135
2.2	0.040	0.038	0.0390	8.3	0.015	0.011	0.0130
2.3	0.041	0.040	0.0405	8.4	0.014	0.012	0.0130
2.4	0.039	0.040	0.0395	8.5	0.014	0.012	0.0130
2.5	0.041	0.039	0.0400	9.0	0.011	0.013	0.0120
3.0	0.040	0.038	0.0390	9.1	0.012	0.014	0.0130
3.1	0.042	0.039	0.0405	9.2	0.011	0.012	0.0115
3.2	0.040	0.038	0.0390	9.3	0.012	0.011	0.0115
3.3	0.038	0.037	0.0375	9.4	0.012	0.012	0.0120
3.4	0.040	0.040	0.0400	9.5	0.011	0.011	0.0110
3.5	0.041	0.038	0.0395	10.0	0.010	0.011	0.0105
4.0	0.040	0.036	0.0380	10.1	0.010	0.012	0.0110
4.1	0.042	0.035	0.0385	10.2	0.009	0.013	0.0110
4.2	0.040	0.034	0.0370	10.3	0.010	0.012	0.0110
4.3	0.041	0.034	0.0375	10.4	0.011	0.012	0.0115
4.4	0.038	0.030	0.0340	10.5	0.010	0.011	0.0105
4.5	0.036	0.032	0.0340	11.0	0.009	0.012	0.0105
5.0	0.034	0.030	0.0320	11.1	0.010	0.011	0.0105
5.1	0.032	0.030	0.0310	11.2	0.009	0.010	0.0095
5.2	0.033	0.029	0.0310	11.3	0.010	0.011	0.0105
5.3	0.030	0.028	0.0290	11.4	0.009	0.011	0.0100
5.4	0.031	0.028	0.0295	11.5	0.010	0.011	0.0105
5.5	0.027	0.027	0.0270	12.0	0.009	0.011	0.0100
6.0	0.024	0.024	0.0240				

Table B12 Study effect of air flow rate of aerosol personal pump at 3, 4, and 5 L/min

PM_{10}					
Flow rate	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
3 L/min	Test 1	0.0366±0.0092	0.0188±0.0012	48.63	45.24±4.80
	Test 2	0.0363±0.0073	0.0211±0.0044	41.85	
4 L/min	Test 1	0.0360±0.0080	0.0190±0.0034	47.30	51.79±6.35
	Test 2	0.0374±0.0091	0.0163±0.0038	56.28	
5 L/min	Test 1	0.0390±0.0080	0.0114±0.0022	70.87	70.39±0.68
	Test 2	0.0391±0.0018	0.0118±0.0009	69.91	

* Number of data points = 24 points for each period

Table B13 Study effect of the initial concentrations of rice bran at 2 times of the original concentration

$PM_{2.5}$							
initial concentrations at 2 times of the original concentration							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.040	0.036	0.0380	6.1	0.027	0.024	0.0255
0.1	0.041	0.039	0.0400	6.2	0.026	0.023	0.0245
0.2	0.042	0.038	0.0400	6.3	0.027	0.023	0.0250
0.3	0.039	0.037	0.0380	6.4	0.025	0.023	0.0240
0.4	0.041	0.039	0.0400	6.5	0.027	0.021	0.0240
0.5	0.040	0.038	0.0390	7.0	0.026	0.022	0.0240
1.0	0.040	0.036	0.0380	7.1	0.025	0.021	0.0230
1.1	0.042	0.038	0.0400	7.2	0.026	0.022	0.0240
1.2	0.042	0.038	0.0400	7.3	0.027	0.022	0.0245
1.3	0.044	0.037	0.0405	7.4	0.026	0.022	0.0240
1.4	0.040	0.039	0.0395	7.5	0.026	0.022	0.0240
1.5	0.041	0.038	0.0395	8.0	0.025	0.021	0.0230
2.0	0.042	0.036	0.0390	8.1	0.025	0.021	0.0230
2.1	0.040	0.035	0.0375	8.2	0.025	0.020	0.0225
2.2	0.041	0.034	0.0375	8.3	0.026	0.020	0.0230
2.3	0.040	0.036	0.0380	8.4	0.025	0.021	0.0230
2.4	0.040	0.035	0.0375	8.5	0.025	0.019	0.0220
2.5	0.040	0.039	0.0395	9.0	0.025	0.019	0.0220
3.0	0.044	0.038	0.0410	9.1	0.026	0.018	0.0220
3.1	0.042	0.037	0.0395	9.2	0.025	0.019	0.0220
3.2	0.040	0.039	0.0395	9.3	0.025	0.019	0.0220
3.3	0.041	0.037	0.0390	9.4	0.025	0.020	0.0225
3.4	0.040	0.035	0.0375	9.5	0.025	0.019	0.0220
3.5	0.039	0.034	0.0365	10.0	0.026	0.018	0.0220
4.0	0.037	0.033	0.0350	10.1	0.024	0.018	0.0210
4.1	0.036	0.034	0.0350	10.2	0.025	0.018	0.0215
4.2	0.035	0.029	0.0320	10.3	0.025	0.019	0.0220
4.3	0.030	0.028	0.0290	10.4	0.026	0.018	0.0220
4.4	0.032	0.030	0.0310	10.5	0.025	0.018	0.0215
4.5	0.031	0.028	0.0295	11.0	0.024	0.018	0.0210
5.0	0.029	0.027	0.0280	11.1	0.024	0.017	0.0205
5.1	0.029	0.027	0.0280	11.2	0.024	0.018	0.0210
5.2	0.028	0.026	0.0270	11.3	0.023	0.019	0.0210
5.3	0.028	0.025	0.0265	11.4	0.024	0.018	0.0210
5.4	0.026	0.025	0.0255	11.5	0.024	0.019	0.0215
5.5	0.025	0.024	0.0245	12.0	0.024	0.019	0.0215
6.0	0.026	0.023	0.0245				

Table B14 Study effect of the initial concentrations of rice bran at 3 times of the original concentration

$PM_{2.5}$							
initial concentrations at 3 times of the original concentration							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.058	0.060	0.0590	6.1	0.041	0.041	0.0410
0.1	0.059	0.061	0.0600	6.2	0.042	0.040	0.0410
0.2	0.058	0.062	0.0600	6.3	0.041	0.040	0.0405
0.3	0.060	0.062	0.0610	6.4	0.041	0.041	0.0410
0.4	0.061	0.063	0.0620	6.5	0.039	0.038	0.0385
0.5	0.063	0.062	0.0625	7.0	0.038	0.038	0.0380
1.0	0.064	0.063	0.0635	7.1	0.037	0.039	0.0380
1.1	0.064	0.062	0.0630	7.2	0.035	0.038	0.0365
1.2	0.062	0.064	0.0630	7.3	0.034	0.037	0.0355
1.3	0.064	0.063	0.0635	7.4	0.034	0.036	0.0350
1.4	0.061	0.063	0.0620	7.5	0.033	0.035	0.0340
1.5	0.062	0.062	0.0620	8.0	0.034	0.034	0.0340
2.0	0.062	0.062	0.0620	8.1	0.033	0.033	0.0330
2.1	0.064	0.061	0.0625	8.2	0.034	0.033	0.0335
2.2	0.062	0.060	0.0610	8.3	0.033	0.031	0.0320
2.3	0.063	0.062	0.0625	8.4	0.033	0.031	0.0320
2.4	0.062	0.062	0.0620	8.5	0.033	0.032	0.0325
2.5	0.063	0.064	0.0635	9.0	0.034	0.030	0.0320
3.0	0.062	0.063	0.0625	9.1	0.032	0.031	0.0315
3.1	0.062	0.063	0.0625	9.2	0.032	0.030	0.0310
3.2	0.060	0.064	0.0620	9.3	0.032	0.029	0.0305
3.3	0.060	0.064	0.0620	9.4	0.031	0.028	0.0295
3.4	0.061	0.065	0.0630	9.5	0.032	0.028	0.0300
3.5	0.060	0.063	0.0615	10.0	0.032	0.029	0.0305
4.0	0.061	0.063	0.0620	10.1	0.032	0.029	0.0305
4.1	0.058	0.060	0.0590	10.2	0.032	0.028	0.0300
4.2	0.052	0.055	0.0535	10.3	0.033	0.029	0.0310
4.3	0.050	0.050	0.0500	10.4	0.033	0.029	0.0310
4.4	0.051	0.052	0.0515	10.5	0.031	0.028	0.0295
4.5	0.050	0.050	0.0500	11.0	0.032	0.028	0.0300
5.0	0.047	0.046	0.0465	11.1	0.032	0.028	0.0300
5.1	0.046	0.048	0.0470	11.2	0.030	0.029	0.0295
5.2	0.045	0.046	0.0455	11.3	0.031	0.028	0.0295
5.3	0.046	0.045	0.0455	11.4	0.030	0.029	0.0295
5.4	0.046	0.044	0.0450	11.5	0.031	0.028	0.0295
5.5	0.043	0.042	0.0425	12.0	0.031	0.029	0.0300
6.0	0.042	0.041	0.0415				

Table B15 Study effect of the initial concentrations of rice bran at 4 times of the original concentration

PM$_{2.5}$							
initial concentrations at 4 times of the original concentration							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.078	0.080	0.0790	6.1	0.048	0.047	0.0475
0.1	0.087	0.081	0.0840	6.2	0.046	0.045	0.0455
0.2	0.080	0.082	0.0810	6.3	0.044	0.044	0.0440
0.3	0.080	0.082	0.0810	6.4	0.043	0.044	0.0435
0.4	0.081	0.023	0.0520	6.5	0.042	0.042	0.0420
0.5	0.082	0.082	0.0820	7.0	0.042	0.041	0.0415
1.0	0.084	0.084	0.0840	7.1	0.041	0.041	0.0410
1.1	0.084	0.084	0.0840	7.2	0.040	0.040	0.0400
1.2	0.083	0.082	0.0825	7.3	0.040	0.038	0.0390
1.3	0.081	0.084	0.0825	7.4	0.042	0.039	0.0405
1.4	0.082	0.083	0.0825	7.5	0.040	0.038	0.0390
1.5	0.080	0.084	0.0820	8.0	0.041	0.037	0.0390
2.0	0.080	0.082	0.0810	8.1	0.040	0.037	0.0385
2.1	0.081	0.084	0.0825	8.2	0.039	0.034	0.0365
2.2	0.082	0.084	0.0830	8.3	0.038	0.033	0.0355
2.3	0.082	0.084	0.0830	8.4	0.038	0.033	0.0355
2.4	0.084	0.083	0.0835	8.5	0.037	0.033	0.0350
2.5	0.083	0.084	0.0835	9.0	0.037	0.034	0.0355
3.0	0.083	0.084	0.0835	9.1	0.036	0.034	0.0350
3.1	0.082	0.082	0.0820	9.2	0.035	0.033	0.0340
3.2	0.082	0.081	0.0815	9.3	0.036	0.034	0.0350
3.3	0.082	0.082	0.0820	9.4	0.036	0.033	0.0345
3.4	0.084	0.080	0.0820	9.5	0.036	0.033	0.0345
3.5	0.081	0.082	0.0815	10.0	0.037	0.033	0.0350
4.0	0.080	0.081	0.0805	10.1	0.037	0.032	0.0345
4.1	0.076	0.076	0.0760	10.2	0.036	0.033	0.0345
4.2	0.072	0.074	0.0730	10.3	0.036	0.033	0.0345
4.3	0.064	0.061	0.0625	10.4	0.035	0.034	0.0345
4.4	0.064	0.060	0.0620	10.5	0.036	0.033	0.0345
4.5	0.062	0.059	0.0605	11.0	0.036	0.033	0.0345
5.0	0.061	0.056	0.0585	11.1	0.036	0.032	0.0340
5.1	0.060	0.055	0.0575	11.2	0.037	0.032	0.0345
5.2	0.055	0.056	0.0555	11.3	0.037	0.033	0.0350
5.3	0.051	0.053	0.0520	11.4	0.038	0.032	0.0350
5.4	0.050	0.050	0.0500	11.5	0.037	0.032	0.0345
5.5	0.051	0.050	0.0505	12.0	0.037	0.033	0.0350
6.0	0.049	0.046	0.0475				

Table B16 Study effect of the initial concentrations of rice bran at 5 times of the original concentration

$PM_{2.5}$							
initial concentrations at 5 times of the original concentration							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.097	0.103	0.1000	6.1	0.069	0.074	0.0715
0.1	0.099	0.105	0.1020	6.2	0.065	0.070	0.0675
0.2	0.098	0.104	0.1010	6.3	0.063	0.069	0.0660
0.3	0.098	0.102	0.1000	6.4	0.062	0.068	0.0650
0.4	0.099	0.105	0.1020	6.5	0.061	0.067	0.0640
0.5	0.100	0.104	0.1020	7.0	0.061	0.067	0.0640
1.0	0.099	0.104	0.1015	7.1	0.060	0.660	0.3600
1.1	0.099	0.104	0.1015	7.2	0.058	0.062	0.0600
1.2	0.100	0.105	0.1025	7.3	0.055	0.061	0.0580
1.3	0.099	0.104	0.1015	7.4	0.054	0.060	0.0570
1.4	0.101	0.102	0.1015	7.5	0.054	0.059	0.0565
1.5	0.099	0.104	0.1015	8.0	0.053	0.058	0.0555
2.0	0.098	0.103	0.1005	8.1	0.053	0.058	0.0555
2.1	0.099	0.105	0.1020	8.2	0.052	0.054	0.0530
2.2	0.100	0.102	0.1010	8.3	0.051	0.056	0.0535
2.3	0.099	0.104	0.1015	8.4	0.051	0.054	0.0525
2.4	0.101	0.106	0.1035	8.5	0.052	0.055	0.0535
2.5	0.099	0.104	0.1015	9.0	0.052	0.055	0.0535
3.0	0.099	0.103	0.1010	9.1	0.051	0.056	0.0535
3.1	0.098	0.103	0.1005	9.2	0.052	0.055	0.0535
3.2	0.099	0.104	0.1015	9.3	0.051	0.054	0.0525
3.3	0.096	0.103	0.0995	9.4	0.050	0.053	0.0515
3.4	0.098	0.103	0.1005	9.5	0.051	0.055	0.0530
3.5	0.096	0.100	0.0980	10.0	0.052	0.055	0.0535
4.0	0.095	0.099	0.0970	10.1	0.051	0.054	0.0525
4.1	0.093	0.950	0.5215	10.2	0.051	0.054	0.0525
4.2	0.090	0.920	0.5050	10.3	0.051	0.054	0.0525
4.3	0.085	0.087	0.0860	10.4	0.052	0.053	0.0525
4.4	0.082	0.085	0.0835	10.5	0.050	0.055	0.0525
4.5	0.080	0.084	0.0820	11.0	0.050	0.054	0.0520
5.0	0.081	0.084	0.0825	11.1	0.051	0.053	0.0520
5.1	0.080	0.082	0.0810	11.2	0.050	0.054	0.0520
5.2	0.078	0.080	0.0790	11.3	0.051	0.055	0.0530
5.3	0.076	0.079	0.0775	11.4	0.050	0.055	0.0525
5.4	0.075	0.080	0.0775	11.5	0.051	0.055	0.0530
5.5	0.072	0.079	0.0755	12.0	0.051	0.055	0.0530
6.0	0.071	0.075	0.0730				

Table B17 Study effect of the initial concentrations of rice bran at original concentration, 2, 3, 4, and 5 times of the original value

$PM_{2.5}$					
Initial concentration	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
original concentration	Test 1	0.0390±0.0080	0.0114±0.0022	70.87	70.39±0.68
	Test 2	0.0391±0.0018	0.0118±0.0009	69.91	
2 times	Test 1	0.0825±0.0029	0.0441±0.0011	46.58	49.10±3.56
	Test 2	0.0801±0.0015	0.0388±0.0030	51.62	
3 times	Test 1	0.1162±0.0024	0.0663±0.0063	42.93	44.49±2.22
	Test 2	0.1214±0.0022	0.0655±0.0024	46.06	
4 times	Test 1	0.1644±0.0013	0.0731±0.0011	55.51	55.38±0.19
	Test 2	0.1582±0.0088	0.0708±0.0011	55.25	
5 times	Test 1	0.1970±0.0016	0.0941±0.0022	52.22	52.41±0.28
	Test 2	0.2012±0.0017	0.0954±0.0017	52.61	

* Number of data points = 24 points for each period

Table B18 Study effect of the initial concentrations of rice bran at 2 times of the original concentration

PM_{10}							
initial concentrations at 2 times of the original concentration							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.083	0.076	0.0795	6.1	0.056	0.050	0.0530
0.1	0.083	0.078	0.0805	6.2	0.056	0.051	0.0535
0.2	0.084	0.078	0.0810	6.3	0.054	0.051	0.0525
0.3	0.084	0.079	0.0815	6.4	0.054	0.049	0.0515
0.4	0.085	0.079	0.0820	6.5	0.052	0.049	0.0505
0.5	0.084	0.080	0.0820	7.0	0.052	0.048	0.0500
1.0	0.085	0.082	0.0835	7.1	0.050	0.047	0.0485
1.1	0.086	0.082	0.0840	7.2	0.051	0.047	0.0490
1.2	0.085	0.081	0.0830	7.3	0.049	0.046	0.0475
1.3	0.085	0.081	0.0830	7.4	0.049	0.046	0.0475
1.4	0.083	0.080	0.0815	7.5	0.048	0.045	0.0465
1.5	0.084	0.081	0.0825	8.0	0.046	0.046	0.0460
2.0	0.084	0.080	0.0820	8.1	0.047	0.045	0.0460
2.1	0.084	0.082	0.0830	8.2	0.045	0.044	0.0445
2.2	0.083	0.080	0.0815	8.3	0.044	0.043	0.0435
2.3	0.082	0.080	0.0810	8.4	0.044	0.043	0.0435
2.4	0.080	0.081	0.0805	8.5	0.045	0.040	0.0425
2.5	0.081	0.082	0.0815	9.0	0.045	0.038	0.0415
3.0	0.083	0.081	0.0820	9.1	0.045	0.038	0.0415
3.1	0.084	0.082	0.0830	9.2	0.045	0.039	0.0420
3.2	0.080	0.080	0.0800	9.3	0.044	0.039	0.0415
3.3	0.077	0.080	0.0785	9.4	0.044	0.038	0.0410
3.4	0.081	0.079	0.0800	9.5	0.045	0.037	0.0410
3.5	0.08	0.080	0.0800	10.0	0.045	0.038	0.0415
4.0	0.073	0.079	0.0760	10.1	0.044	0.038	0.0410
4.1	0.070	0.071	0.0705	10.2	0.044	0.038	0.0410
4.2	0.070	0.069	0.0695	10.3	0.043	0.037	0.0400
4.3	0.068	0.064	0.0660	10.4	0.043	0.037	0.0400
4.4	0.068	0.064	0.0660	10.5	0.044	0.037	0.0405
4.5	0.066	0.062	0.0640	11.0	0.043	0.036	0.0395
5.0	0.065	0.061	0.0630	11.1	0.043	0.037	0.0400
5.1	0.064	0.060	0.0620	11.2	0.042	0.036	0.0390
5.2	0.060	0.058	0.0590	11.3	0.043	0.036	0.0395
5.3	0.059	0.055	0.0570	11.4	0.043	0.036	0.0395
5.4	0.059	0.054	0.0565	11.5	0.043	0.036	0.0395
5.5	0.058	0.055	0.0565	12.0	0.043	0.037	0.0400
6.0	0.057	0.054	0.0555				

Table B19 Study effect of the initial concentrations of rice bran at 3 times of the original concentration

PM$_{10}$							
initial concentrations at 3 times of the original concentration							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.110	0.120	0.1150	6.1	0.090	0.096	0.0930
0.1	0.110	0.124	0.1170	6.2	0.089	0.093	0.0910
0.2	0.112	0.126	0.1190	6.3	0.088	0.090	0.0890
0.3	0.115	0.121	0.1180	6.4	0.085	0.090	0.0875
0.4	0.115	0.120	0.1175	6.5	0.083	0.089	0.0860
0.5	0.115	0.122	0.1185	7.0	0.083	0.084	0.0835
1.0	0.116	0.122	0.1190	7.1	0.082	0.083	0.0825
1.1	0.116	0.120	0.1180	7.2	0.080	0.080	0.0800
1.2	0.118	0.122	0.1200	7.3	0.076	0.076	0.0760
1.3	0.118	0.123	0.1205	7.4	0.075	0.750	0.4125
1.4	0.118	0.120	0.1190	7.5	0.073	0.072	0.0725
1.5	0.118	0.121	0.1195	8.0	0.072	0.071	0.0715
2.0	0.116	0.121	0.1185	8.1	0.071	0.070	0.0705
2.1	0.118	0.122	0.1200	8.2	0.070	0.070	0.0700
2.2	0.117	0.124	0.1205	8.3	0.071	0.069	0.0700
2.3	0.118	0.124	0.1210	8.4	0.070	0.068	0.0690
2.4	0.118	0.122	0.1200	8.5	0.069	0.065	0.0670
2.5	0.118	0.123	0.1205	9.0	0.067	0.066	0.0665
3.0	0.118	0.123	0.1205	9.1	0.066	0.066	0.0660
3.1	0.117	0.122	0.1195	9.2	0.065	0.065	0.0650
3.2	0.116	0.120	0.1180	9.3	0.065	0.065	0.0650
3.3	0.117	0.119	0.1180	9.4	0.064	0.066	0.0650
3.4	0.116	0.119	0.1175	9.5	0.064	0.065	0.0645
3.5	0.117	0.120	0.1185	10.0	0.063	0.064	0.0635
4.0	0.118	0.115	0.1165	10.1	0.063	0.064	0.0635
4.1	0.115	0.118	0.1165	10.2	0.092	0.065	0.0785
4.2	0.112	0.115	0.1135	10.3	0.063	0.064	0.0635
4.3	0.098	0.113	0.1055	10.4	0.064	0.064	0.0640
4.4	0.099	0.112	0.1055	10.5	0.063	0.063	0.0630
4.5	0.098	0.110	0.1040	11.0	0.062	0.064	0.0630
5.0	0.095	0.110	0.1025	11.1	0.063	0.064	0.0635
5.1	0.095	0.109	0.1020	11.2	0.062	0.065	0.0635
5.2	0.094	0.106	0.1000	11.3	0.062	0.064	0.0630
5.3	0.094	0.104	0.0990	11.4	0.062	0.063	0.0625
5.4	0.092	0.102	0.0970	11.5	0.063	0.064	0.0635
5.5	0.090	0.101	0.0955	12.0	0.062	0.063	0.0625
6.0	0.090	0.098	0.0940				

Table B20 Study effect of the initial concentrations of rice bran at 4 times of the original concentration

PM_{10}							
initial concentrations at 4 times of the original concentration							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.161	0.160	0.1605	6.1	0.130	0.129	0.1295
0.1	0.162	0.161	0.1615	6.2	0.127	0.125	0.1260
0.2	0.165	0.159	0.1620	6.3	0.113	0.122	0.1175
0.3	0.166	0.159	0.1625	6.4	0.110	0.120	0.1150
0.4	0.165	0.161	0.1630	6.5	0.110	0.118	0.1140
0.5	0.166	0.160	0.1630	7.0	0.109	0.113	0.1110
1.0	0.165	0.158	0.1615	7.1	0.106	0.112	0.1090
1.1	0.164	0.159	0.1615	7.2	0.105	0.110	0.1075
1.2	0.165	0.160	0.1625	7.3	0.101	0.105	0.1030
1.3	0.164	0.159	0.1615	7.4	0.100	0.104	0.1020
1.4	0.165	0.161	0.1630	7.5	0.095	0.103	0.0990
1.5	0.164	0.162	0.1630	8.0	0.093	0.097	0.0950
2.0	0.165	0.161	0.1630	8.1	0.092	0.095	0.0935
2.1	0.163	0.160	0.1615	8.2	0.092	0.095	0.0935
2.2	0.164	0.161	0.1625	8.3	0.091	0.092	0.0915
2.3	0.163	0.162	0.1625	8.4	0.090	0.091	0.0905
2.4	0.163	0.162	0.1625	8.5	0.087	0.085	0.0860
2.5	0.164	0.160	0.1620	9.0	0.084	0.081	0.0825
3.0	0.166	0.159	0.1625	9.1	0.083	0.08	0.0815
3.1	0.165	0.160	0.1625	9.2	0.081	0.076	0.0785
3.2	0.164	0.159	0.1615	9.3	0.08	0.075	0.0775
3.3	0.167	0.158	0.1625	9.4	0.079	0.074	0.0765
3.4	0.165	0.159	0.1620	9.5	0.075	0.073	0.0740
3.5	0.164	0.160	0.1620	10.0	0.074	0.073	0.0735
4.0	0.165	0.160	0.1625	10.1	0.075	0.072	0.0735
4.1	0.160	0.158	0.1590	10.2	0.074	0.070	0.0720
4.2	0.159	0.156	0.1575	10.3	0.073	0.070	0.0715
4.3	0.156	0.155	0.1555	10.4	0.073	0.070	0.0715
4.4	0.155	0.153	0.1540	10.5	0.074	0.071	0.0725
4.5	0.152	0.152	0.1520	11.0	0.072	0.071	0.0715
5.0	0.150	0.152	0.1510	11.1	0.073	0.070	0.0715
5.1	0.149	0.150	0.1495	11.2	0.072	0.070	0.0710
5.2	0.145	0.146	0.1455	11.3	0.072	0.071	0.0715
5.3	0.141	0.143	0.1420	11.4	0.073	0.070	0.0715
5.4	0.140	0.140	0.1400	11.5	0.072	0.070	0.0710
5.5	0.135	0.135	0.1350	12.0	0.072	0.070	0.0710
6.0	0.132	0.130	0.1310				

Table B21 Study effect of the initial concentrations of rice bran at 5 times of the original concentration

PM_{10}							
initial concentrations at 5 times of the original concentration							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.192	0.198	0.1950	6.1	0.146	0.145	0.1455
0.1	0.195	0.199	0.1970	6.2	0.143	0.142	0.1425
0.2	0.197	0.200	0.1985	6.3	0.136	0.139	0.1375
0.3	0.197	0.202	0.1995	6.4	0.135	0.135	0.1350
0.4	0.198	0.203	0.2005	6.5	0.132	0.136	0.1340
0.5	0.198	0.204	0.2010	7.0	0.131	0.135	0.1330
1.0	0.198	0.202	0.2000	7.1	0.130	0.132	0.1310
1.1	0.199	0.203	0.2010	7.2	0.130	0.134	0.1320
1.2	0.198	0.201	0.1995	7.3	0.128	0.133	0.1305
1.3	0.198	0.201	0.1995	7.4	0.125	0.129	0.1270
1.4	0.199	0.202	0.2005	7.5	0.123	0.128	0.1255
1.5	0.197	0.202	0.1995	8.0	0.122	0.126	0.1240
2.0	0.197	0.201	0.1990	8.1	0.122	0.122	0.1220
2.1	0.196	0.202	0.1990	8.2	0.118	0.119	0.1185
2.2	0.196	0.204	0.2000	8.3	0.112	0.118	0.1150
2.3	0.197	0.203	0.2000	8.4	0.110	0.115	0.1125
2.4	0.198	0.202	0.2000	8.5	0.108	0.112	0.1100
2.5	0.199	0.200	0.1995	9.0	0.108	0.111	0.1095
3.0	0.198	0.200	0.1990	9.1	0.105	0.110	0.1075
3.1	0.198	0.201	0.1995	9.2	0.101	0.105	0.1030
3.2	0.197	0.202	0.1995	9.3	0.102	0.102	0.1020
3.3	0.195	0.198	0.1965	9.4	0.100	0.103	0.1015
3.4	0.196	0.200	0.1980	9.5	0.099	0.100	0.0995
3.5	0.197	0.201	0.1990	10.0	0.098	0.098	0.0980
4.0	0.195	0.199	0.1970	10.1	0.095	0.095	0.0950
4.1	0.192	0.190	0.1910	10.2	0.094	0.094	0.0940
4.2	0.182	0.185	0.1835	10.3	0.095	0.096	0.0955
4.3	0.177	0.176	0.1765	10.4	0.095	0.095	0.0950
4.4	0.168	0.171	0.1695	10.5	0.094	0.096	0.0950
4.5	0.165	0.170	0.1675	11.0	0.094	0.095	0.0945
5.0	0.160	0.168	0.1640	11.1	0.093	0.094	0.0935
5.1	0.158	0.164	0.1610	11.2	0.092	0.095	0.0935
5.2	0.155	0.159	0.1570	11.3	0.092	0.094	0.0930
5.3	0.156	0.157	0.1565	11.4	0.093	0.094	0.0935
5.4	0.152	0.152	0.1520	11.5	0.092	0.094	0.0930
5.5	0.150	0.150	0.1500	12.0	0.092	0.095	0.0935
6.0	0.148	0.149	0.1485				

Table B22 Study effect of the initial concentrations of rice bran at original concentration, 2, 3, 4, and 5 times of the original value

PM$_{10}$					
Initial concentration	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
original concentration	Test 1	0.0390±0.0080	0.0114±0.0022	70.87	70.39±0.68
	Test 2	0.0391±0.0018	0.0118±0.0009	69.91	
2 times	Test 1	0.0825±0.0029	0.0441±0.0011	46.58	49.10±3.56
	Test 2	0.0801±0.0015	0.0388±0.0030	51.62	
3 times	Test 1	0.1162±0.0024	0.0663±0.0063	42.93	44.49±2.22
	Test 2	0.1214±0.0022	0.0655±0.0024	46.06	
4 times	Test 1	0.1644±0.0013	0.0731±0.0011	55.51	55.38±0.19
	Test 2	0.1582±0.0088	0.0708±0.0011	55.25	
5 times	Test 1	0.1970±0.0016	0.0941±0.0022	52.22	52.41±0.28
	Test 2	0.2012±0.0017	0.0954±0.0017	52.61	

* Number of data points = 24 points for each period

Table B23 Study effect of the commercial fiber (3M 8210) for filtration

$PM_{2.5}$							
commercial fiber (3M 8210)							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.022	0.020	0.0210	6.1	0.013	0.013	0.0130
0.1	0.023	0.023	0.0230	6.2	0.013	0.013	0.0130
0.2	0.026	0.023	0.0245	6.3	0.012	0.013	0.0125
0.3	0.025	0.025	0.0250	6.4	0.012	0.012	0.0120
0.4	0.024	0.023	0.0235	6.5	0.012	0.011	0.0115
0.5	0.024	0.024	0.0240	7.0	0.011	0.011	0.0110
1.0	0.022	0.022	0.0220	7.1	0.011	0.012	0.0115
1.1	0.023	0.023	0.0230	7.2	0.012	0.011	0.0115
1.2	0.024	0.024	0.0240	7.3	0.013	0.011	0.0120
1.3	0.021	0.023	0.0220	7.4	0.011	0.011	0.0110
1.4	0.022	0.024	0.0230	7.5	0.011	0.012	0.0115
1.5	0.023	0.024	0.0235	8.0	0.012	0.011	0.0115
2.0	0.022	0.023	0.0225	8.1	0.012	0.011	0.0115
2.1	0.024	0.023	0.0235	8.2	0.011	0.011	0.0110
2.2	0.023	0.024	0.0235	8.3	0.011	0.012	0.0115
2.3	0.021	0.022	0.0215	8.4	0.011	0.011	0.0110
2.4	0.023	0.002	0.0125	8.5	0.011	0.011	0.0110
2.5	0.023	0.023	0.0230	9.0	0.010	0.011	0.0105
3.0	0.021	0.023	0.0220	9.1	0.010	0.011	0.0105
3.1	0.022	0.022	0.0220	9.2	0.009	0.010	0.0095
3.2	0.023	0.023	0.0230	9.3	0.009	0.010	0.0095
3.3	0.022	0.022	0.0220	9.4	0.009	0.009	0.0090
3.4	0.022	0.023	0.0225	9.5	0.008	0.010	0.0090
3.5	0.023	0.022	0.0225	10.0	0.007	0.011	0.0090
4.0	0.023	0.022	0.0225	10.1	0.008	0.011	0.0095
4.1	0.020	0.020	0.0200	10.2	0.007	0.009	0.0080
4.2	0.020	0.021	0.0205	10.3	0.007	0.009	0.0080
4.3	0.019	0.021	0.0200	10.4	0.006	0.009	0.0075
4.4	0.018	0.020	0.0190	10.5	0.007	0.009	0.0080
4.5	0.018	0.020	0.0190	11.0	0.007	0.009	0.0080
5.0	0.017	0.019	0.0180	11.1	0.007	0.018	0.0125
5.1	0.016	0.019	0.0175	11.2	0.006	0.009	0.0075
5.2	0.015	0.018	0.0165	11.3	0.006	0.009	0.0075
5.3	0.015	0.016	0.0155	11.4	0.006	0.009	0.0075
5.4	0.014	0.015	0.0145	11.5	0.005	0.008	0.0065
5.5	0.014	0.014	0.0140	12.0	0.006	0.009	0.0075
6.0	0.013	0.014	0.0135				

Table B24 Study effect of two series SF fibers for filtration

$PM_{2.5}$							
Two series filter holder							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.020	0.020	0.0200	6.1	0.016	0.015	0.0155
0.1	0.021	0.021	0.0210	6.2	0.017	0.016	0.0165
0.2	0.023	0.022	0.0225	6.3	0.015	0.015	0.0150
0.3	0.024	0.024	0.0240	6.4	0.016	0.015	0.0155
0.4	0.024	0.023	0.0235	6.5	0.015	0.014	0.0145
0.5	0.024	0.022	0.0230	7.0	0.014	0.013	0.0135
1.0	0.025	0.022	0.0235	7.1	0.015	0.013	0.0140
1.1	0.024	0.022	0.0230	7.2	0.014	0.013	0.0135
1.2	0.025	0.021	0.0230	7.3	0.013	0.012	0.0125
1.3	0.026	0.023	0.0245	7.4	0.013	0.013	0.0130
1.4	0.023	0.024	0.0235	7.5	0.013	0.012	0.0125
1.5	0.024	0.024	0.0240	8.0	0.012	0.012	0.0120
2.0	0.025	0.024	0.0245	8.1	0.012	0.013	0.0125
2.1	0.024	0.024	0.0240	8.2	0.011	0.012	0.0115
2.2	0.025	0.023	0.0240	8.3	0.010	0.011	0.0105
2.3	0.025	0.024	0.0245	8.4	0.010	0.011	0.0105
2.4	0.023	0.023	0.0230	8.5	0.010	0.012	0.0110
2.5	0.024	0.024	0.0240	9.0	0.010	0.011	0.0105
3.0	0.025	0.024	0.0245	9.1	0.011	0.012	0.0115
3.1	0.022	0.023	0.0225	9.2	0.010	0.011	0.0105
3.2	0.023	0.023	0.0230	9.3	0.010	0.010	0.0100
3.3	0.022	0.022	0.0220	9.4	0.009	0.010	0.0095
3.4	0.024	0.024	0.0240	9.5	0.009	0.010	0.0095
3.5	0.022	0.023	0.0225	10.0	0.009	0.009	0.0090
4.0	0.022	0.020	0.0210	10.1	0.010	0.009	0.0095
4.1	0.020	0.020	0.0200	10.2	0.009	0.008	0.0085
4.2	0.019	0.019	0.0190	10.3	0.009	0.009	0.0090
4.3	0.019	0.019	0.0190	10.4	0.009	0.009	0.0090
4.4	0.017	0.018	0.0175	10.5	0.009	0.009	0.0090
4.5	0.018	0.019	0.0185	11.0	0.010	0.009	0.0095
5.0	0.019	0.018	0.0185	11.1	0.008	0.010	0.0090
5.1	0.018	0.016	0.0170	11.2	0.009	0.009	0.0090
5.2	0.018	0.017	0.0175	11.3	0.009	0.009	0.0090
5.3	0.018	0.017	0.0175	11.4	0.009	0.008	0.0085
5.4	0.017	0.017	0.0170	11.5	0.009	0.009	0.0090
5.5	0.017	0.016	0.0165	12.0	0.009	0.009	0.0090
6.0	0.017	0.016	0.0165				

Table B25 Study effect of Whatman No.1 filter for filtration

PM$_{2.5}$							
Whatman No.1							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.022	0.020	0.0210	6.1	0.014	0.016	0.0150
0.1	0.023	0.022	0.0225	6.2	0.013	0.016	0.0145
0.2	0.023	0.024	0.0235	6.3	0.013	0.015	0.0140
0.3	0.024	0.025	0.0245	6.4	0.013	0.015	0.0140
0.4	0.024	0.023	0.0235	6.5	0.012	0.016	0.0140
0.5	0.024	0.024	0.0240	7.0	0.012	0.015	0.0135
1.0	0.024	0.024	0.0240	7.1	0.013	0.015	0.0140
1.1	0.023	0.023	0.0230	7.2	0.012	0.014	0.0130
1.2	0.023	0.024	0.0235	7.3	0.012	0.014	0.0130
1.3	0.023	0.024	0.0235	7.4	0.012	0.013	0.0125
1.4	0.024	0.023	0.0235	7.5	0.011	0.014	0.0125
1.5	0.023	0.024	0.0235	8.0	0.011	0.013	0.0120
2.0	0.024	0.024	0.0240	8.1	0.010	0.012	0.0110
2.1	0.025	0.023	0.0240	8.2	0.010	0.013	0.0115
2.2	0.024	0.025	0.0245	8.3	0.011	0.012	0.0115
2.3	0.024	0.025	0.0245	8.4	0.011	0.011	0.0110
2.4	0.024	0.025	0.0245	8.5	0.012	0.012	0.0120
2.5	0.024	0.024	0.0240	9.0	0.011	0.012	0.0115
3.0	0.023	0.025	0.0240	9.1	0.010	0.013	0.0115
3.1	0.023	0.023	0.0230	9.2	0.011	0.012	0.0115
3.2	0.024	0.024	0.0240	9.3	0.011	0.012	0.0115
3.3	0.021	0.022	0.0215	9.4	0.010	0.011	0.0105
3.4	0.022	0.023	0.0225	9.5	0.011	0.011	0.0110
3.5	0.023	0.022	0.0225	10.0	0.011	0.012	0.0115
4.0	0.023	0.020	0.0215	10.1	0.010	0.011	0.0105
4.1	0.002	0.020	0.0110	10.2	0.011	0.011	0.0110
4.2	0.019	0.019	0.0190	10.3	0.011	0.011	0.0110
4.3	0.017	0.019	0.0180	10.4	0.011	0.011	0.0110
4.4	0.018	0.018	0.0180	10.5	0.011	0.011	0.0110
4.5	0.017	0.019	0.0180	11.0	0.011	0.012	0.0115
5.0	0.016	0.018	0.0170	11.1	0.011	0.010	0.0105
5.1	0.016	0.018	0.0170	11.2	0.010	0.011	0.0105
5.2	0.016	0.017	0.0165	11.3	0.011	0.012	0.0115
5.3	0.015	0.017	0.0160	11.4	0.011	0.011	0.0110
5.4	0.016	0.018	0.0170	11.5	0.011	0.012	0.0115
5.5	0.015	0.017	0.0160	12.0	0.011	0.012	0.0115
6.0	0.013	0.016	0.0145				

Table B26 Study effect of the commercial fiber (3M 8210), two series SF fibers, and Whatman No.1 for filtration

$PM_{2.5}$					
Types of filter	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
Whatman No.1	Test 1	0.0234±0.0009	0.0108±0.0005	53.77	52.16±2.27
	Test 2	0.0235±0.0014	0.0116±0.0032	50.56	
3M 8210	Test 1	0.0228±0.0012	0.0071±0.0012	69.09	63.50±7.91
	Test 2	0.0221±0.0043	0.0093±0.0008	57.91	
Two series SF fibers	Test 1	0.0236±0.0014	0.0093±0.0007	60.46	59.42±1.47
	Test 2	0.0228±0.0013	0.0095±0.0010	58.38	

* Number of data points = 24 points for each period

Table B27 Study effect of the commercial fiber (3M 8210) for filtration

PM_{10}							
commercial fiber (3M 8210)							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.041	0.043	0.0420	6.1	0.027	0.025	0.0260
0.1	0.042	0.044	0.0430	6.2	0.025	0.022	0.0235
0.2	0.044	0.042	0.0430	6.3	0.025	0.021	0.0230
0.3	0.045	0.042	0.0435	6.4	0.024	0.022	0.0230
0.4	0.045	0.040	0.0425	6.5	0.022	0.020	0.0210
0.5	0.046	0.041	0.0435	7.0	0.021	0.019	0.0200
1.0	0.046	0.043	0.0445	7.1	0.020	0.018	0.0190
1.1	0.045	0.042	0.0435	7.2	0.019	0.017	0.0180
1.2	0.044	0.042	0.0430	7.3	0.019	0.015	0.0170
1.3	0.045	0.041	0.0430	7.4	0.018	0.015	0.0165
1.4	0.044	0.040	0.0420	7.5	0.016	0.014	0.0150
1.5	0.045	0.042	0.0435	8.0	0.015	0.013	0.0140
2.0	0.045	0.042	0.0435	8.1	0.015	0.013	0.0140
2.1	0.043	0.040	0.0415	8.2	0.014	0.012	0.0130
2.2	0.044	0.041	0.0425	8.3	0.014	0.011	0.0125
2.3	0.044	0.041	0.0425	8.4	0.013	0.012	0.0125
2.4	0.043	0.040	0.0415	8.5	0.014	0.011	0.0125
2.5	0.044	0.041	0.0425	9.0	0.013	0.010	0.0115
3.0	0.045	0.043	0.0440	9.1	0.013	0.012	0.0125
3.1	0.043	0.042	0.0425	9.2	0.013	0.011	0.0120
3.2	0.045	0.041	0.0430	9.3	0.012	0.010	0.0110
3.3	0.044	0.042	0.0430	9.4	0.012	0.010	0.0110
3.4	0.043	0.040	0.0415	9.5	0.012	0.010	0.0110
3.5	0.044	0.410	0.2270	10.0	0.011	0.009	0.0100
4.0	0.045	0.037	0.0410	10.1	0.011	0.009	0.0100
4.1	0.040	0.036	0.0380	10.2	0.010	0.009	0.0095
4.2	0.039	0.035	0.0370	10.3	0.009	0.009	0.0090
4.3	0.039	0.034	0.0365	10.4	0.010	0.008	0.0090
4.4	0.037	0.033	0.0350	10.5	0.009	0.007	0.0080
4.5	0.036	0.030	0.0330	11.0	0.009	0.008	0.0085
5.0	0.035	0.031	0.0330	11.1	0.010	0.008	0.0090
5.1	0.032	0.030	0.0310	11.2	0.009	0.008	0.0085
5.2	0.031	0.029	0.0300	11.3	0.009	0.008	0.0085
5.3	0.031	0.029	0.0300	11.4	0.008	0.007	0.0075
5.4	0.030	0.027	0.0285	11.5	0.009	0.008	0.0085
5.5	0.029	0.026	0.0275	12.0	0.009	0.008	0.0085
6.0	0.028	0.025	0.0265				

Table B28 Study effect of two series SF fibers for filtration

PM_{10}							
Two series filter holder							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.040	0.044	0.0420	6.1	0.028	0.034	0.0310
0.1	0.041	0.043	0.0420	6.2	0.026	0.030	0.0280
0.2	0.042	0.042	0.0420	6.3	0.026	0.028	0.0270
0.3	0.044	0.045	0.0445	6.4	0.027	0.025	0.0260
0.4	0.044	0.040	0.0420	6.5	0.025	0.024	0.0245
0.5	0.045	0.042	0.0435	7.0	0.024	0.025	0.0245
1.0	0.043	0.043	0.0430	7.1	0.025	0.023	0.0240
1.1	0.044	0.044	0.0440	7.2	0.230	0.020	0.1250
1.2	0.045	0.042	0.0435	7.3	0.023	0.021	0.0220
1.3	0.043	0.044	0.0435	7.4	0.024	0.022	0.0230
1.4	0.042	0.044	0.0430	7.5	0.022	0.021	0.0215
1.5	0.042	0.043	0.0425	8.0	0.021	0.022	0.0215
2.0	0.044	0.045	0.0445	8.1	0.020	0.020	0.0200
2.1	0.045	0.040	0.0425	8.2	0.019	0.02	0.0195
2.2	0.043	0.042	0.0425	8.3	0.018	0.021	0.0195
2.3	0.043	0.046	0.0445	8.4	0.019	0.019	0.0190
2.4	0.044	0.045	0.0445	8.5	0.018	0.020	0.0190
2.5	0.042	0.044	0.0430	9.0	0.017	0.02	0.0185
3.0	0.044	0.045	0.0445	9.1	0.017	0.019	0.018
3.1	0.043	0.042	0.0425	9.2	0.015	0.018	0.0165
3.2	0.043	0.043	0.0430	9.3	0.014	0.016	0.0150
3.3	0.040	0.045	0.0425	9.4	0.013	0.015	0.0140
3.4	0.042	0.042	0.0420	9.5	0.012	0.014	0.0130
3.5	0.043	0.041	0.0420	10.0	0.012	0.014	0.0130
4.0	0.042	0.044	0.0430	10.1	0.011	0.015	0.0130
4.1	0.039	0.038	0.0385	10.2	0.012	0.013	0.0125
4.2	0.038	0.037	0.0375	10.3	0.012	0.012	0.0120
4.3	0.036	0.035	0.0355	10.4	0.011	0.013	0.0120
4.4	0.035	0.035	0.0350	10.5	0.012	0.012	0.0120
4.5	0.034	0.034	0.0340	11.0	0.011	0.013	0.0120
5.0	0.034	0.035	0.0345	11.1	0.012	0.012	0.0120
5.1	0.033	0.034	0.0335	11.2	0.011	0.013	0.0120
5.2	0.032	0.036	0.0340	11.3	0.011	0.012	0.0115
5.3	0.032	0.035	0.0335	11.4	0.010	0.012	0.0110
5.4	0.032	0.034	0.033	11.5	0.011	0.013	0.0120
5.5	0.030	0.035	0.0325	12.0	0.011	0.012	0.0115
6.0	0.029	0.034	0.0315				

Table B29 Study effect of Whatman No.1 filter for filtration

PM_{10}							
Whatman No.1							
Time (hr)	PM concentration (mg/m^3)			Time (hr)	PM concentration (mg/m^3)		
	Test 1	Test 2	Average		Test 1	Test 2	Average
0.0	0.040	0.042	0.0410	6.1	0.027	0.028	0.0275
0.1	0.040	0.041	0.0405	6.2	0.026	0.025	0.0255
0.2	0.039	0.042	0.0405	6.3	0.026	0.023	0.0245
0.3	0.040	0.045	0.0425	6.4	0.025	0.022	0.0235
0.4	0.039	0.043	0.0410	6.5	0.024	0.021	0.0225
0.5	0.041	0.044	0.0425	7.0	0.025	0.023	0.0240
1.0	0.042	0.043	0.0425	7.1	0.024	0.020	0.0220
1.1	0.042	0.043	0.0425	7.2	0.023	0.020	0.0215
1.2	0.041	0.042	0.0415	7.3	0.022	0.019	0.0205
1.3	0.041	0.044	0.0425	7.4	0.023	0.019	0.0210
1.4	0.042	0.043	0.0425	7.5	0.022	0.018	0.0200
1.5	0.040	0.044	0.0420	8.0	0.021	0.018	0.0195
2.0	0.041	0.044	0.0425	8.1	0.020	0.017	0.0185
2.1	0.039	0.043	0.0410	8.2	0.020	0.018	0.0190
2.2	0.039	0.042	0.0405	8.3	0.019	0.018	0.0185
2.3	0.040	0.043	0.0415	8.4	0.019	0.017	0.0180
2.4	0.040	0.044	0.0420	8.5	0.018	0.016	0.0170
2.5	0.039	0.043	0.0410	9.0	0.016	0.017	0.0165
3.0	0.040	0.044	0.0420	9.1	0.017	0.017	0.0170
3.1	0.039	0.042	0.0405	9.2	0.016	0.016	0.0160
3.2	0.038	0.043	0.0405	9.3	0.016	0.015	0.0155
3.3	0.036	0.041	0.0385	9.4	0.015	0.015	0.0150
3.4	0.037	0.040	0.0385	9.5	0.015	0.015	0.0150
3.5	0.038	0.039	0.0385	10.0	0.015	0.014	0.0145
4.0	0.039	0.040	0.0395	10.1	0.014	0.014	0.0140
4.1	0.035	0.038	0.0365	10.2	0.015	0.014	0.0145
4.2	0.033	0.036	0.0345	10.3	0.014	0.013	0.0135
4.3	0.032	0.035	0.0335	10.4	0.013	0.013	0.0130
4.4	0.032	0.034	0.0330	10.5	0.015	0.012	0.0135
4.5	0.030	0.033	0.0315	11.0	0.014	0.013	0.0135
5.0	0.032	0.033	0.0325	11.1	0.015	0.013	0.0140
5.1	0.031	0.034	0.0325	11.2	0.014	0.013	0.0135
5.2	0.030	0.032	0.0310	11.3	0.014	0.013	0.0135
5.3	0.029	0.031	0.0300	11.4	0.014	0.012	0.0130
5.4	0.029	0.030	0.0295	11.5	0.014	0.013	0.0135
5.5	0.028	0.029	0.0285	12.0	0.014	0.013	0.0135
6.0	0.028	0.027	0.0275				

Table B30 Study effect of the commercial fiber (3M 8210)**,** two series SF fibers, and Whatman No.1 for filtration

PM_{10}					
Types of filter	Test	Avg. initial concentration (Mean±SD)	Avg. final concentration (Mean±SD)	%RE	% Avg. RE (Mean±SD)
Whatman No.1	Test 1	0.0400±0.0015	0.0149±0.0012	62.45	64.72±3.21
	Test 2	0.0426±0.0015	0.0141±0.0015	66.99	
3M 8210	Test 1	0.0442±0.0012	0.0104±0.0016	76.40	77.44±1.47
	Test 2	0.0429±0.0737	0.0089±0.0013	84.14	
Two series SF fibers	Test 1	0.0429±0.0014	0.0121±0.0017	71.78	69.95±2.60
	Test 2	0.0432±0.0016	0.0138±0.0021	68.11	

* Number of data points = 24 points for each period

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