To the Graduate Council:

I am submitting herewith a thesis written by Bruce Alan Phillips entitled "Characterization of the Particle Collection Efficiency of Melt-Blown Media at High Air Velocity: Particle Bounce and the Effects of Tackifier Filter Adhesive." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.

Wayne Davis, Major Professor

We have read this thesis
and recommend its acceptance:

Accepted for the Council:

Associate Vice Chancellor and
Dean of The Graduate School

CHARACTERIZATION OF THE PARTICLE COLLECTION EFFICIENCY OF MELT-BLOWN MEDIA AT HIGH AIR VELOCITY: PARTICLE BOUNCE AND THE EFFECTS OF TACKIFIER FILTER ADHESIVE

A Thesis

Presented for the Master of Science Degree

The University of Tennessee, Knoxville

Bruce Alan Phillips

December 1995

DEDICATION

This thesis is dedicated

to the two women in my life:

Ellise and Miriam

Thank you for your

love and support.

I would also like to

dedicate it in memory of

Mrs. Emma Reynolds Dunn,

whose wisdom and inspiration

have profoundly influenced my life.

ACKNOWLEDGMENTS

I would like to thank my major professor, Dr. Wayne T. Davis, for his patience, commitment and time. He has been a continual example of the type of professional which I am striving to become. I appreciate all of his work and effort in the completion of my graduate studies. I would also like to thank the other members of my committee, Dr. Terry Miller, and Dr. Maureen Dever, for their comments and advice.

This research was funded in part by the National Science Foundation, Division of Biological Engineering Systems (Contract number 9415329 Dever). Filters were manufactured within the laboratories of TANDEC (the Textiles and Nonwovens Development Center) and the efficiency testing was conducted in the Department of Civil and Environmental Engineering at the University of Tennessee.

ABSTRACT

Many commercially available indoor air filters are currently being marketed with topically applied tackifier filter adhesives. The concept is as old as the mucous coated cilia in the human respiratory tract. The idea is that a fibrous filter's capture efficiency may be improved by applying a sticky substance to the individual dry fibers. However, little information is available in the literature concerning the application of tackifiers and their effectiveness on decreasing particle penetration through filters. Therefore, it is of scientific value to investigate the efficacy of such tackifiers over a variety of operating air velocities, especially in light of the increasing concern for indoor air quality.

This thesis presents the results of an investigation in which polypropylene melt-blown media were manufactured at a variety of operating conditions, to produce media which might be suitable for use in indoor air quality filters. The objectives of the research were to determine the efficiencies of the media, both as manufactured, and after application of a commercially available tackifier, at velocities ranging from 3 to 375 cm/s and to compare the measured results to filtration theory. The filter media were prepared at the Textiles and Nonwovens Development Center (TANDEC) and tested for filtration efficiency in the Air Quality Laboratory housed in the Department of Civil and Environmental Engineering at the University of Tennessee, Knoxville. Efficiencies were determined using both cold, polydispersed dioctylpthalate (DOP), as well as monodispersed latex particles (0.6 to 3.0 μm) using an ASTM

1215 test method. At the higher velocities, typical of those used in indoor air filters, the experimental efficiencies of the untreated media, using dry particles were significantly less than both the DOP and theoretical efficiencies. This is believed to be due to the kinetic energy of the particles which resulted in particle bounce. Empirical corrections were developed as a function of the kinetic energy to account for the decreased efficiency due to particle bounce and are presented.

On the media which were coated with various loadings of tackifier, the results showed that the efficiencies at high velocities were improved. This is believed to be due to the reduction in particle bounce. The efficiencies at low velocities were unchanged even though larger effective fiber diameters resulted from application of the tackifier.

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LIST OF ABBREVIATIONS

American Society of Heating Refrigeration and Air Conditioning Engineers .... ASHRAE
Absolute Temperature .... T
Air Velocity V
Air Viscosity .... μ_g
Centimeters per Second .... cm/sec
Cubic Feet per Minute .... cfm
Cubic Meters per Minute .... m^3/min
Cunningham Correction Factor .... K_c
Dioctylpthalate .... DOP
Effective Fiber Diameter .... D_{eff}
Environmental Protection Agency .... EPA
Error Function .... erf
Experimental Singe Fiber Impaction Efficiency .... η'_I
Fiber Diameter .... D_f
Fiber Thickness L
Fiber Inhomogeneity Factor .... ε
Filter Areal Density .... W_f
Fine Suspended Particulate .... FSP
Geometric Standard Deviation .... GSD, σ
Gram .... g
High Efficiency Particulate Air Filter .... HEPA
Inches .... in
Interception Parameter .... R
Joules .... J
Kinetic Energy .... Ek
Kuwabara Hydrodynamic Factor .... K
Lower Respiratory Tract .... LRT
Melt Flow Rate .... MFR

Milli-Volts	mV
Micron	µm
Multi-Channel Analyzer	MCA
Optical Particle Counter	OPC
Overall Filter Efficiency	η_0
Overall Filter Penetration	Pn_0
Packing Density	c
Particle Density	ρ_p
Particle Diameter	D_p
Particle Diffusivity	$\mathcal{D}$
Peclet Number	Pe
Poly-Styrene Latex Spheres	PSL
Pressure Drop Across Filter	ΔP
Pounds per Square Inch Gage	psig
Respirable Suspended Particulate	RSP
Reynolds Number	Re
Scanning Electron Microscope	SEM
Single Fiber Diffusion Efficiency	η_D
Single Fiber Impaction Efficiency	η_I
Single Fiber Interception Efficiency	η_R
Single Fiber Overall Efficiency	η_S
Solidarity Factor	S
Standard Cubic Feet per Hour	scfh
Stokes Number	ψ
Textiles and Nonwoven Development Center	TANDEC
Upper Respiratory Tract	URT
Volts	V

CHAPTER 1

INTRODUCTION

The use of fibrous air filters dates back well over two thousand years (Davies, 1973). Moreover, the concept of improving their collection efficiencies by application of a tacky substance is as old as the modern human respiratory system and its mucous coated cilia. It is only of relatively recent history that the application of fibrous filters and tackifier filter adhesives toward improvement of indoor air quality has resulted in a resurgence of research and development. Traditionally, commercial and residential heating, ventilating, and air conditioning (HVAC) filters were designed to remove large debris such as pet hair, dust, and lint, and were very inefficient at removing the smaller micrometer-sized particles such as mold or pollen. Potentially adverse health effects presented by these smaller-sized particles demonstrate the importance of improved indoor air quality, and the use of improved HVAC filtration media to achieve it (Phillips et al., 1995).

Since most HVAC filters (both pleated and non-pleated) operate at relatively high air velocities, this thesis focuses on the phenomenon which tends to occur on the surface of filter fibers where particles impact into them at high kinetic energy. This phenomenon, known as particle bounce, leads to a progressive decrease in collection efficiency as a function of increasing particle kinetic energy. This phenomenon is cited throughout the literature, but not investigated in any great detail anywhere. It was reported to be at least partly responsible for the notoriously low efficiencies of the indoor air filters reported by Davis et al. (1994). The investigation of topically applied tackifier filter adhesive as a possible solution to dampen the particle bounce phenomenon is therefore investigated in detail herein.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This section provides a general background for understanding the process of aerosol filtration by fibrous filters, and how it can be related to the application of air filtration in an indoor Heating, Ventilation, and Air Conditioning (HVAC) system. The review starts with a brief historical perspective on aerosol filtration and then relates the importance of aerosol filtration to the impact of airborne pollutants on the human respiratory system. The development of current theoretical concepts in fibrous filtration of aerosols is then discussed. This is followed by a discussion of the conventional wisdom concerning particle adhesion in the inertial impaction regime.

The theories which have been already reviewed by previous authors are only cited as literature. Lengthy equations, especially those no longer in use, and their derivations have been avoided in this section. All mathematical treatment of theory relevant to this research effort is included in the following chapter.

2.2 Background of Air Filtration by Fibrous Filters

To begin an understanding of air filtration, one must first distinguish the difference between air filtration and air cleaning. Air cleaning refers to a less efficient process of particulate removal for industrial gases with a high dust concentration. The cleaning is accomplished by the use of cyclones, scrubbers, sedimentation tanks, oiled gauze's and packs of granules or shapes, such as raschig rings, and electrostatic precipitators (Davies, 1973). Filtration is used to give specially cleaned air for a relatively clean gas, such as atmospheric air for air conditioning. The collection of particles in the first case and initially in the second proceeds only rarely by a screening action because the particles are much smaller than the gaps between the fibers (Strauss, 1966). Small particles in low concentrations must be aerodynamically captured.

Air filtration, like liquid scrubbing, captures particles by collecting bodies. The gas stream passing through the filter or scrubber takes the particles close to these collecting bodies and then a number of short range mechanisms accomplish the actual collection. In any particular case the relative importance of these short range mechanisms varies with the relative size and velocity of the particles, with the collecting body. Davies (1973) suggests that to obtain more efficient, that is to say better than 95% removal of particles in the 0.1 to 1 µm diameter range, there is no substitute for fibrous filters.

The development of air filtration dates back over two thousand years, as the dust problem in Roman mines is well documented (Davies 1973). Hippocrates in 500 B.C. stressed that the air in mines and that encountered in certain trades was highly detrimental to health. The ancient Egyptians had already perceived that silicate dust produced by the cutting of construction stone caused respiratory disease (Meyer, 1983). Near the time of Christ, prominent physicians, both Egyptian and Roman reported on the hazards of dust exposure. Pliny the Elder noted in 23 A.D. that stonemasons and asbestos miners could not work without masks. Not surprisingly, workmen have used cloths to cover the nose and mouth for centuries, and Leonardo da Vinci (1452-1518) even mentions wet cloths as a protection against fumes used in warfare. The first recorded filtering respirator was in 1814 when Brisé Fradin used a box filled with cotton which had a breathing tube going to the mouth, with the nostrils being plugged with cotton (Davies, 1973).

The clairvoyance of Da Vinci has been recognized in many fields of science, and the same might be said for the field of aerosol filtration. Indeed, nothing has provided the stimulus for respirator design and research like the evil ambitions of chemical warfare. The first large-scale resort to chemical warfare by the Germans in 1915 employed the use of phosgene and chlorine. Since these could be readily adsorbed by respirators using canisters of activated carbon, a search was made for means of penetrating the gas filter. Early research discovered that particulate could not be filtered out by carbon, as could gases. Consequently, the Germans sought to penetrate the charcoal filter with aerosols of arsenical smokes. By the end of WW I in 1918, particulate filters had appeared in military gas masks.

Better protection simply encouraged the development of more sinister chemical munitions, this time producing aerosols 0.2 to 0.5 μm in diameter. Hence, large amounts of active material penetrated the filters readily and inflicted alarming respiratory symptoms. At this time, between wars, considerable effort to improve the particulate filter was exerted, and all kinds of fibrous materials were tried without much understanding of the principles of filtration. Many respirator patents exist between the wars which reveal the complete lack of understanding of the mode of action.

Interestingly, it was the Germans, Albrecht (1931) and Kaufmann (1936) who made the original theoretical approaches to aerosol filtration by fibrous pads (Davies, 1973). At the beginning of WW II, both the particulate filter and the dispersal of arsenical smokes had become more effective.

The continuing menace of chemical munitions continues to drive filtration research to this day (Hood, 1993). However, the commercial demand for filters is also increasing to protect human beings as well as mechanical, microelectronic and biological equipment in manufacture and use. Market attractiveness has led the automobile manufacturing industry into devoting increased resources to the development of high efficiency air filters for passenger cabins (Murphy, 1994; Eleftherakis, 1994). Moreover, it is this enclosed environment, or indoor air quality, that has received much devoted research in the context of protecting human health (Wadden and Scheff, 1983; Walsh et al., 1984; Meyer, 1983).

2.3 Particle Deposition in the Human Respiratory Tract

In developing any filtration study, it is important to understand and characterize the particulates considered to be harmful to human health. Clearly it is easy to imagine the adverse health effects of a chemical toxin encountered on the battlefield as previously described. But what about particulates encountered in our homes or offices? To help answer the above question, one must first understand the role of the human respiratory tract as a target organ.

The lungs, which have an average internal surface area of 70 square meters, are continuously exposed to the external environment (Bates, 1972). The branching airways, which start as a single tube about 2.5 cm in diameter, end as ducts only half a millimeter in diameter. Yet there are more than half-a-million of these. The air sacs, called alveoli, are very thin in order to permit fast diffusion of oxygen to the blood, and they lie at the end of the airway system. Figure 2-1 helps the reader to visualize the various components of the human respiratory system.

The entire respiratory system is equipped with a very good defense network to stop incoming particulate matter (Bates, 1972). The nose is known to be very efficient at trapping large particles, and prevents particles 20 to 50 µm from entering the lungs. The nose and the large airways possess small hairs on their surfaces called cilia. Coated with a layer of sticky mucus, they are capable of removing considerable quantities of dirt from the lungs. Deep in the lung, wandering cells called macrophages can pick up and digest, and even remove and store particles from the alveolar surfaces. They are believed to represent an important defense line against bacterial invasion. They probably remove particles of carbon or silica through the walls of the alveolus, and such particles may finally end up being stored, for the life of the individual, in lymphatic glands situated at the root of the lung. More soluble particles might end up in the blood stream and be eliminated through the kidneys.

Figure 2-2 shows the deposition rate of particles in the human lung (Bates, 1972). The figure shows the fraction of inhaled particles which will be deposited in either the upper respiratory tract (URT) or the lower respiratory tract (LRT) in human subjects. Almost all particles between 10 and 100 microns in size will settle in the upper respiratory tract; many of these will be retained in the nose. It is also apparent that an increasing

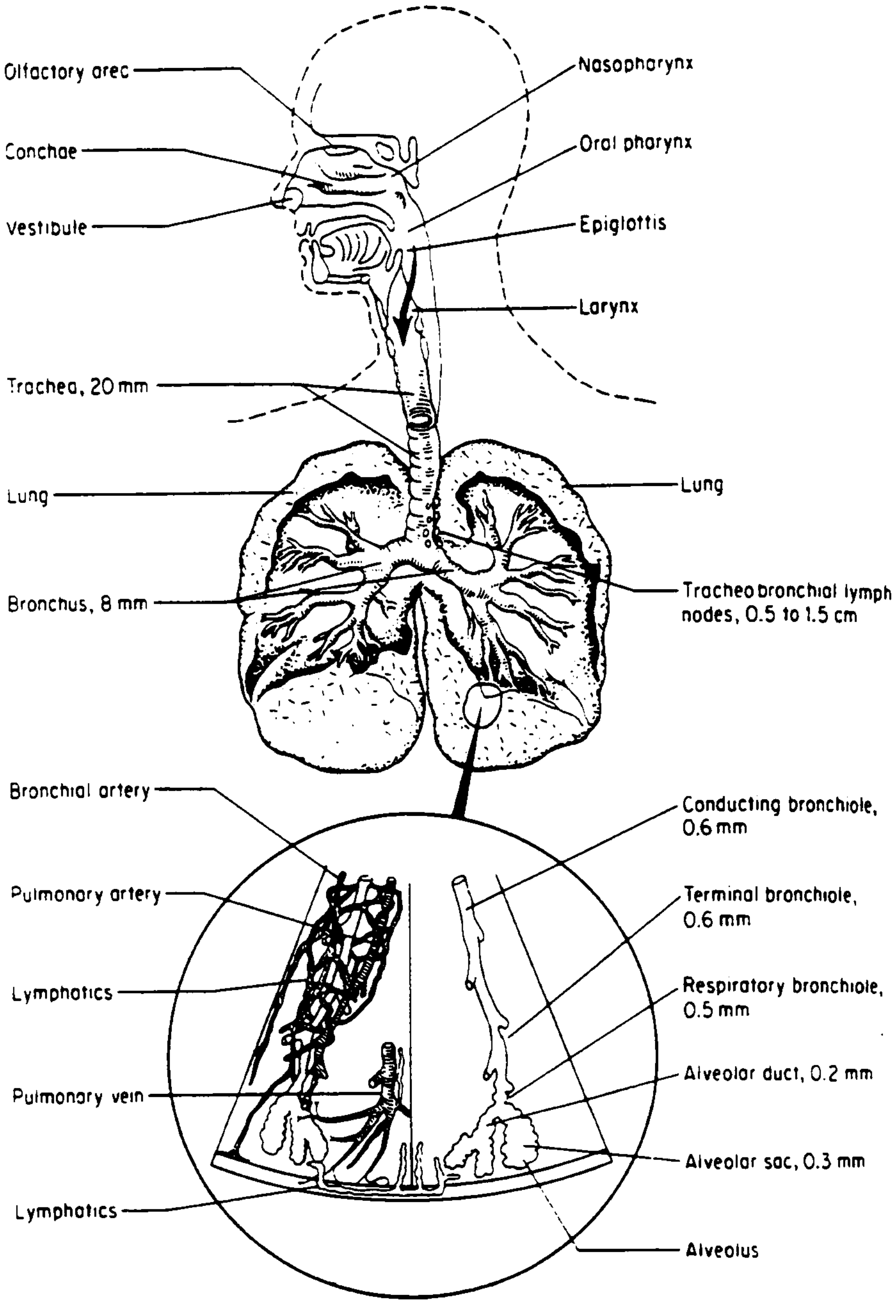

Figure 2-1. The Human Respiratory System (From Meyer, 1983)

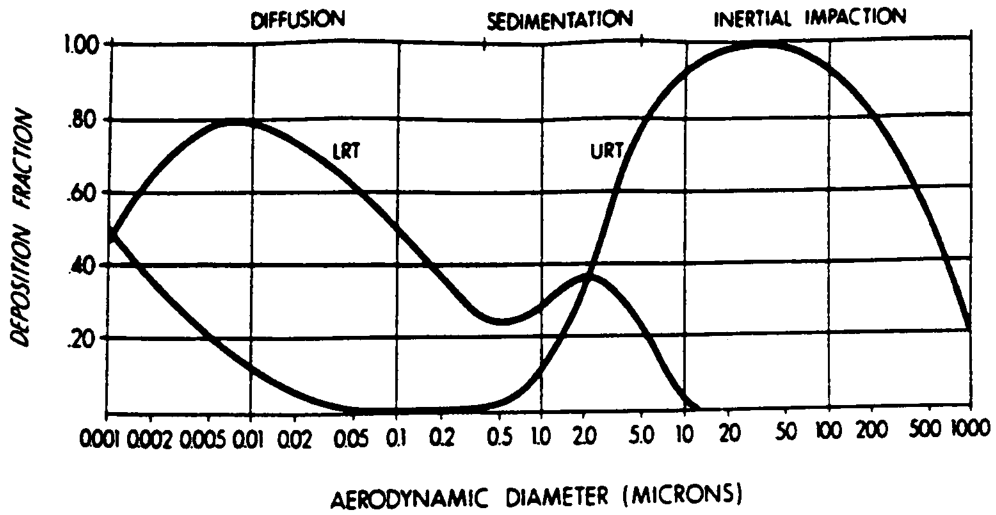

Figure 2-2. Deposition Rate of Particles in the Human Lung

fraction of particles between 0.5 and 0.01 µm will be laid down deep in the lung in the lower respiratory tract. Particles smaller than 0.01 µm have a lower deposition rate in the lung. Meyer (1983) states that particles with a size between 0.1 to 5.0 µm constitutes the most important group for this study because they enter the respiratory tract and penetrate deep into the lung. This particle size is commonly called fine suspended particulate (FSP) matter or respirable particles (RSP). EPA has defined respirable particulate as less than 10.0 µm aerodynamic diameter. The aerodynamic diameter of the particle refers to its actual diameter which, in the presence of water vapor, may be rather larger than the physical size of the particle in dry air. It is defined as the diameter of a sphere with unit density (density of water) that will settle in still air at the same rate as the particle in question (Cooper and Alley, 1986). Depending on their biological, physical, and chemical properties, these particles may dissolve and enter the bloodstream, wash out with the mucus, or be carried to the lung lymph nodes where they may become embedded for life.

Inhaled particles that deposit at various specific sites within the respiratory tract can initiate lesions at those sites, which can contribute to acute or chronic disease (Lippmann et al., 1981). The particles also can migrate from their sites of deposition to other sites within or beyond the respiratory tract by clearance processes, and from there can reach other tissues, where disease processes can take place. The effects of deposited particles on respiratory tract airways may depend on the pattern of deposition at specific sites and the amount deposited in each region as a whole. Within larger airways, it has been observed that the sites where the particle deposition is greatest (e.g., the larynx and the branches in the central bronchi) are also the sites where primary cancers are most commonly found. Common lung diseases are Chronic bronchitis, emphysema, bronchiolitis, lung cancer, pulmonary fibrosis.

Aerosols consist of colloidal particles suspended in a gas, where the colloid may be either liquid or solid (Webster's New World Dictionary, 1980). The word particulate denotes both organic and inorganic materials (Meyer, 1983). Small filaments and particles up to 0.01 µm in size are called smoke; particles for 0.1 µm to the size of sand grains are called dust. Household dust contains a variety of biological, organic, and inorganic agents; these may include such diverse items as mites, viruses, bacteria, asbestos fibers, or human sebum. The chemical composition changes with the seasons (Takeushi et al., 1974). Highway dust is largely inorganic and contains a variety of elements. The eight most important metals are lead, copper, zinc, iron, magnesium, chromium, nickel, and manganese. Urban particulates contain inorganic material from many industrial sources as well as organic materials. The latter include pesticides and such biological materials as pollen, bacteria, and viruses.

Airborne particles of biological origin can evoke several responses by the person who encounters them. An example is fungal spores, which can cause both infections and allergies (Walsh et al., 1984). One bacillus in 50 m^3 of air is sufficient to cause pulmonary tuberculosis. Likewise, allergic people will react violently to just one microspore of ragweed pollen (Meyer, 1983). This same author lists the most common allergens as house dust, animal products, molds, bacteria, chemicals, and pollen. The active ingredients in house dust are proteins and polysaccharides from pollen, dead mites, animal feces, hair, and other biological matter. The most important clinical syndromes are allergic rhinitis, bronchial asthma, alveolar infiltrates with blood eosinophilia, and alveolitis. Today, clean-room technology makes it possible to produce microbe-free air in virus labs, space shuttles, electronics factories, and the like, but only if people are kept out of these rooms or are detoxified with masks and clothing. Figure 2-3 shows the characteristics of particles and particle dispersoids encountered in the environment. The reader may wish to compare the size ranges of typical aerosols or particulates to those sizes previously defined as damaging to the lungs. Also note the size range defined to be within effective air filtration range.

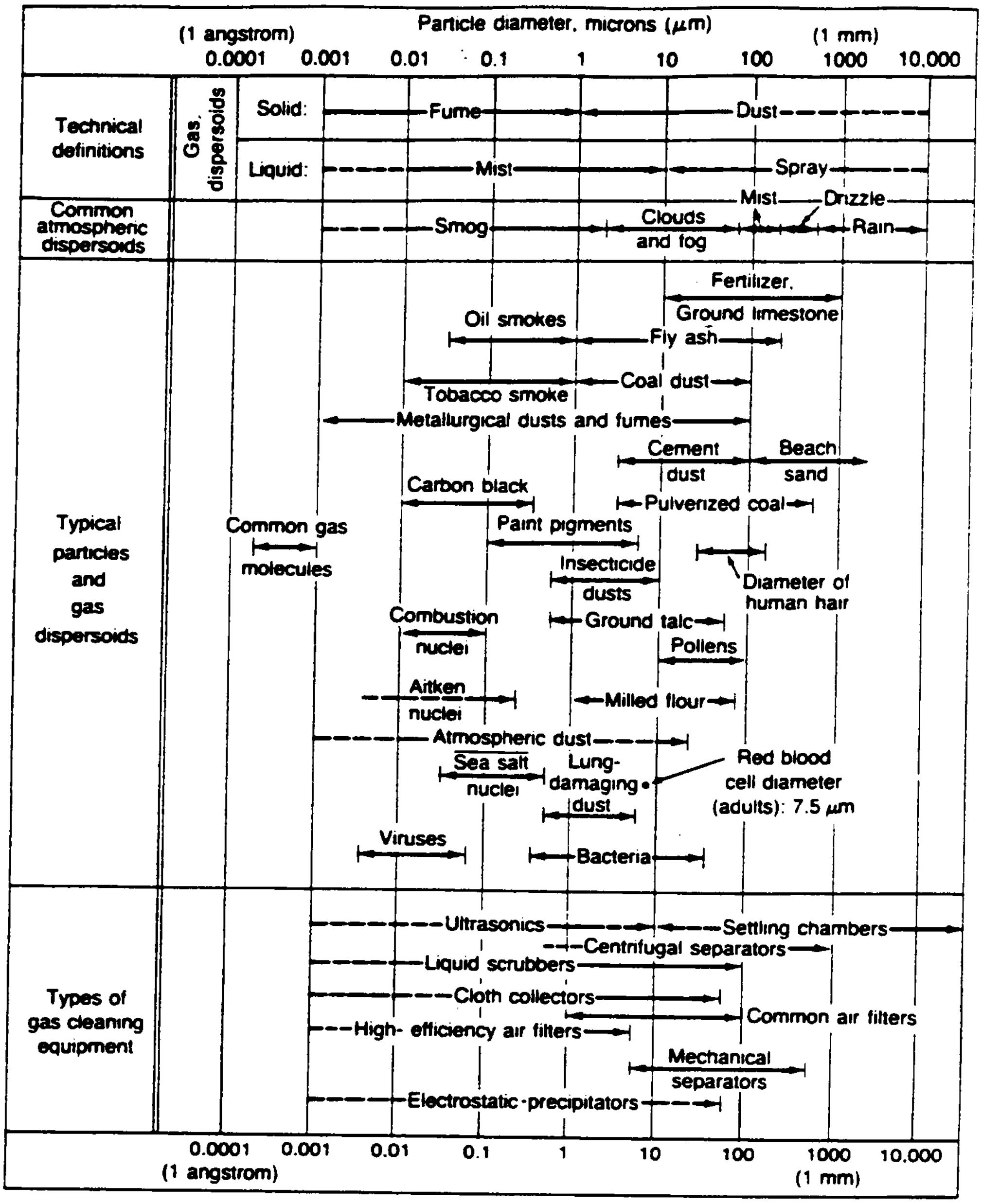

Figure 2-3. Characteristics of Particles and Particle Dispersoids (From Cooper and Alley, 1986)

2.4 Current ASHRAE Filter Test Methods

The type of filter to use depends on the particular applications under consideration (Wadden and Scheff, 1983). Mass collection efficiency, collection efficiency for submicron particles, and pressure drop are all factors in filter evaluation. ASHRAE has recommended several standard tests for evaluating filter performance (ASHRAE , 1979). *Weight arrestance* is the mass collection efficiency of a filter for a standard synthetic dust. However, many particles which may cause soiling and/or be physiologically harmful are smaller than those in the standard synthetic dust, often in the submicron size range. The *DOP penetration test* (dioctyl phthalate) measures the percent penetration of 0.3 μm DOP particles through the filter. The *dust spot efficiency* test measures the rate of light change in glass fiber sampling filters upstream and downstream of the filter being tested. Untreated atmospheric dust is used, and the resulting filter efficiency reflects the efficacy of the filter in preventing wall discoloration. The *dust holding capacity test* measures the integrated amount of dust held on the filter up to the time the test was terminated, either at the maximum pressure drop specified by the manufacturer, or when two consecutive measures of arrestance fall below 85% of maximum mass collection efficiency. Figure 2-4 indicates performance characteristics for some typical dry filter media (Wadden and Scheff, 1983).

Filter Media Type	ASHRAE Weight Arrestance (%)	ASHRAE Atmospheric Dust Spot Efficiency (%)	MIL-STD 282 DOP Efficiency (%)	ASHRAE Dust-Holding Capacity (grams per 1700 m^3/h cell	Superficial Duct Velocity [m/sec (fpm)]	Pressure Drop mm H_2O/mm Thickness	
						Initial	Final
Finer open cell foams and textile denier nonwovens	70-80	15-30	0	180-425			
Thin, paperlike mats of glass fibers, cellulose	80-90	20-35	0	90-180			
Mats of glass fiber multi-ply cellulose, wool felt	85-90	25-40	5-10	90-180			
Mats of 5-10 μm fibers, 6-12 mm thickness	90-95	40-60	15-25	270-540	2.54(500)	0.028[c]	0.083
Mats of 3-5 μm fibers, 6-20 mm thickness	>95	60-80	35-40	180-450			
Mats of 1-4 μm fibers, mixture of various fibers and asbestos	>95	80-90	50-55	180-360			
Mats of 0.5-2 μm fibers (usually glass fibers)	NA[b]	90-98	75-90	90-270	2.54(500)	0.054[c]	0.100
Wet laid papers of mostly glass and asbestos fibers < 1 μm diameter (HEPA filters)	NA	NA	95 95-99.999 99.97	500-1000	0.64-1.3(125-250) 0.64-1.3(125-250)	0.039-0.060[d] 0.073-0.153[d]	0.174-0.255
Membrane filters (membranes of cellulose acetate, nylon, etc. having holes 1 μm diameter or less)	NA	NA	~100	NA			

[a]ASHRAE (1979).
[b]NA indicates that test method cannot be applied to this type of filter.
[c]Typical total thickness = 305 mm (12 in.).
[d]Typical total thickness = 78-300 mm (3-12 in.).

Figure 2-4. Efficiency of Particle Air Filters (From Wadden and Scheff, 1983)

2.5 Contemporary Concepts in Aerosol Filtration

Davies (1952) provided a very detailed historical accounting of aerosol filtration up to 1948. His textbook (1973) also provides the framework for modern concepts in aerosol filtration theory. A brief review of this development is in order.

Of interest, of course, is that early in the theoretical understanding of aerosol filtration mechanisms it was discovered that the finer fibers would provide for higher efficiency. Asbestos fibers were used at first for filters by themselves, since these fibers were very fine, and later were incorporated in paper filters which could be pleated. Even though the asbestos was later replaced as the filter medium, the pleating is still employed in high efficiency filters today, while still providing for low air resistance across the filter medium itself (Chen, 1995).

Brownian motion of the smaller particles had been recognized as an important collection mechanism in filtration, and was linked with diffusion since Einstein's work in 1905 (Davies, 1973). It was also recognized that aerosol filters did not operate like sieves. What was not entirely understood was the reasons why larger particles, which showed no significant Brownian motion, could be filtered. This mechanism was not yet clearly associated with particle inertia. The pioneer Albrecht (1931) was cited previously by Davies as the first to address this problem. The solutions led to inaccuracies, however, since they were based on ideal, instead of viscous fluid flow. The concept of interception was first introduced by Langmuir (1942), as a geometrical relationship. The theory was that if the center of the particle were to pass the surface of the fiber at a distance less than the particle radius, collision, or filtration would result. The concept of inertial deposition was previously elaborated upon by Sell (1931). Kaufman (1936) was the first to bring the concept of brownian diffusion and inertial deposition into a cohesive filtration theory. However, this brilliant effort was still flawed as it considered only ideal fluid flow. The problem with using the ideal concept, is that it is completely controlled by the inertia of the fluid which is assumed to be without viscosity (Davies, 1973). Real fluids act like ideal fluids except near solid surfaces where the Reynolds number is large. Air flowing past a filter fiber with a small Reynolds number will have different streamlines. So it is the difference in streamline geometry caused by the respective ideal and viscous fluid flow theories that will significantly affect particle collection. Interception and Brownian diffusion are therefore less effective in viscous flow than they would be in ideal flow. Inertial impaction is even more affected.

Davies (1973) presents the first cohesive theory which combines the mechanisms of diffusion, interception and inertial impaction. Figure 2-5 presents the conceptual function of each of these mechanisms. However, the concept of inertial impaction was never accepted by Langmuir (1942, 1944). His experimental work had indicated that penetration of filters increased when the face velocity increased, as was required by his theory of filtration by diffusion and interception (Davies, 1973). It turns out that the aerosols he tested tended to "blow through filters...as flow was increased, so that the penetration depended on the adhesion of particles to the fibers and on the breaking up of aggregates, factors which were not allowed for in single

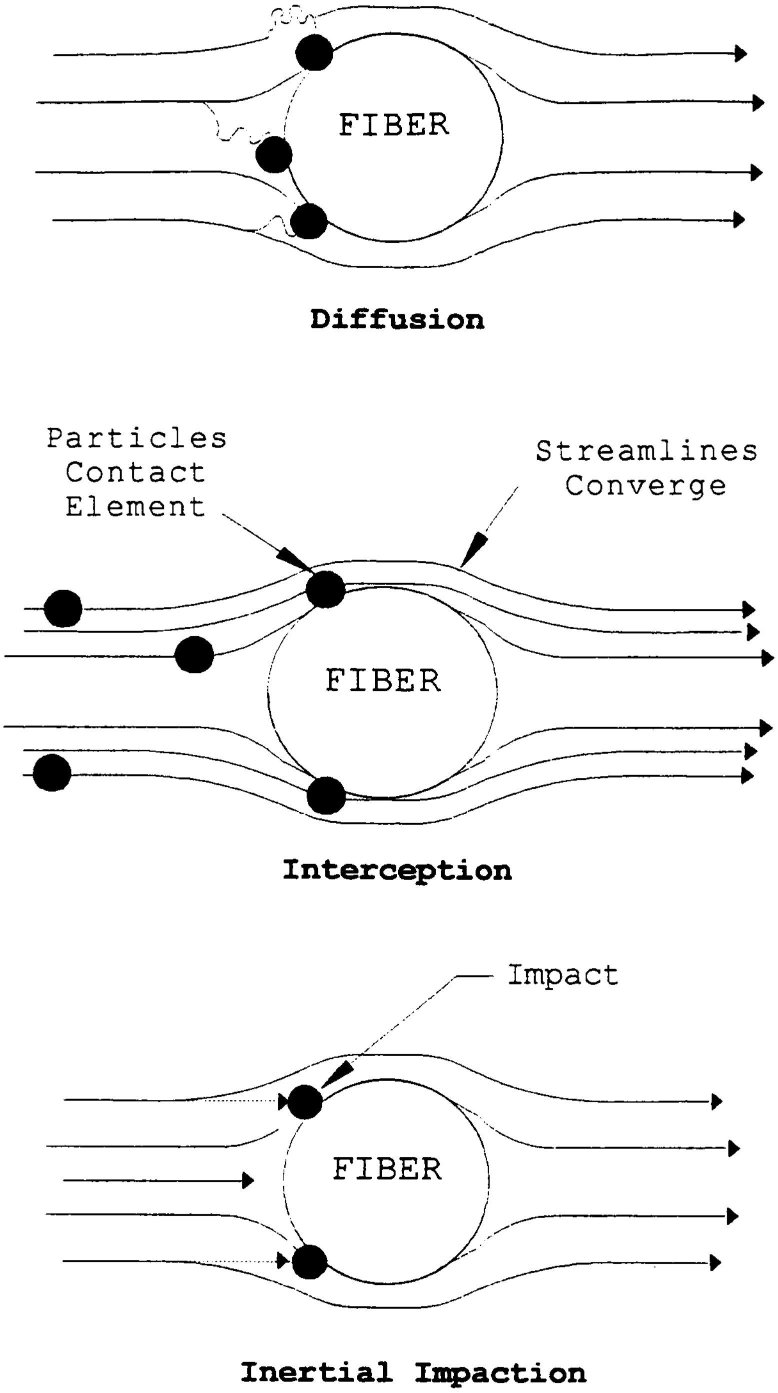

Figure 2-5. Conceptual Diagram of Diffusion, Interception, and Inertial Impaction Collection Mechanisms

fiber collision theory which expressed penetration as a function of diffusion towards, interception by, and inertial impaction upon the fibers by the particles," (Davies, 1973). This same author goes on to state that "this complication could have been avoided by using aerosols of liquid particles (of extremely low vapor pressure so that evaporation was negligible). Such particles remain attached to fibers, due to surface tension with the result that the filtration of such aerosol is entirely a matter of collision dynamics."

Kuwabara (1959) solved the viscous flow Navier-Stokes equations of fluid mechanics in two dimensions to give the distribution of velocity around a cylinder transverse to the flow. By drawing an imaginary coaxial boundary around a cylinder, the filter solidity, or packing density, can be made equal to that of the coaxial cylinders. Based on the assumption of vanishing vorticity on the outer boundary, Kuwabara obtained expressions for the stream function and velocity components from which the "Kuwabara hydrodynamic factor" was derived. The Kuwabara flow field provides a better representation of the flow around filter fibers than the Happel (1959) flow field around filter fibers and has therefore been used more widely in filtration analyses (Fuchs and Stechkina, 1963; Pich, 1965; Stechkina and Fuchs, 1966; Stechkina et al., 1969; Yeh and Liu, 1974a). Aside from his well known publication in 1959, Kuwabara's theoretical development is also well discussed in both Davies (1973), and Lee and Liu (1982). The Kuwabara hydrodynamic factor is a key component in existing filtration theory today, and will be introduced later.

One of the difficulties that remained in the filtration theories until 1963 concerned the treatment of the neighboring fiber interference effect (Lee and Liu, 1982). A second theoretical difficulty has been related to the treatment of the nonideal effects in fiber orientation. The random orientation of fibers and the inhomogeneity of the fibers cause the flow for real filters to deviate from the ideal flow patterns assumed theoretically. Pich (1990) studied the maximal penetration of aerosol filters using the mechanisms of diffusion, interception and gravitational deposition on both granular and fibrous beds, and was able to discern no appreciable differences in the maximal penetrations between the Happel and Kuwabara theories.

In the region of maximum penetrating particle size, the predominant filtration mechanisms are diffusion and interception. Liu and Rubow (1986), and Lee and Liu (1980, 1982) studied the combined mechanisms of diffusion and interception and concluded that "the simplest way to combine the two terms with reasonable accuracy is to add the two individual [single fiber] efficiencies to obtain the combined efficiency. This practice is based on the assumption that only one mechanism is predominant, the contribution made by the other mechanism being small." These researchers studied an empirical correlation on the basis of real filters being made of fibers that are randomly oriented, rather than perpendicular to the plane as adopted in their model. Often times, fibers are not uniformly distributed and phenomena such as channel flow and shadowing can occur. The existing theories take into account the nonideal characteristics of the fibrous filters by defining an empirical factor such as effective fiber diameter factor (Davies, 1952), inhomogeneity factor (Stechkina et al., 1969), or effective fiber length (Yeh and Liu, 1973b). This factor is obtained by comparing the experimental pressure drop and that predicted by the flow field. Using Dacron filter media, Lee and Liu (1982) arrived at the interception and diffusion equations which were used for this thesis and which will be outlined in a later section. An inhomogeneity factor of 1.6 was derived from their experimental results. The filtration theory for the study was found to be successful in correlating filtration efficiency in the region of maximum penetrating particle size with good accuracy. It was also found that their approximations were better at representing the filter solidity dependence of the filtration efficiency than the other comparable theories.

In Figure 2-5 it was shown that inertial impaction occurs as high-inertia particles leave the streamlines flowing around each individual fiber. Taking the case of an ideal fluid as the simplest, Figure 2-6 (a) helps better explain this mechanism. Upon separation from the flowstream, if the collector, or fiber, is within the respective stopping distance, or limiting trajectory of the high inertia particle, it will be collected. Many researchers studied the impaction efficiency's relation to the stopping distance (Strauss, 1966). Although approached independently, all were able to relate the limiting trajectory, and ultimately the impaction efficiency, directly to an inertial impaction parameter also known as Stokes number. There were slight variations in the results of each researcher and this has been shown to be due to Reynolds number. Figure 2-6 (b) shows a viscous fluid and may help to visualize the physical effect of Reynolds number, which is most pronounced in the inertial impaction regime. Strauss stated that "at an Re of 0.2 (viscous flow) a three percent disturbance occurs at a distance of 100 fiber diameters upstream, while when Re = 2000 (ideal flow),

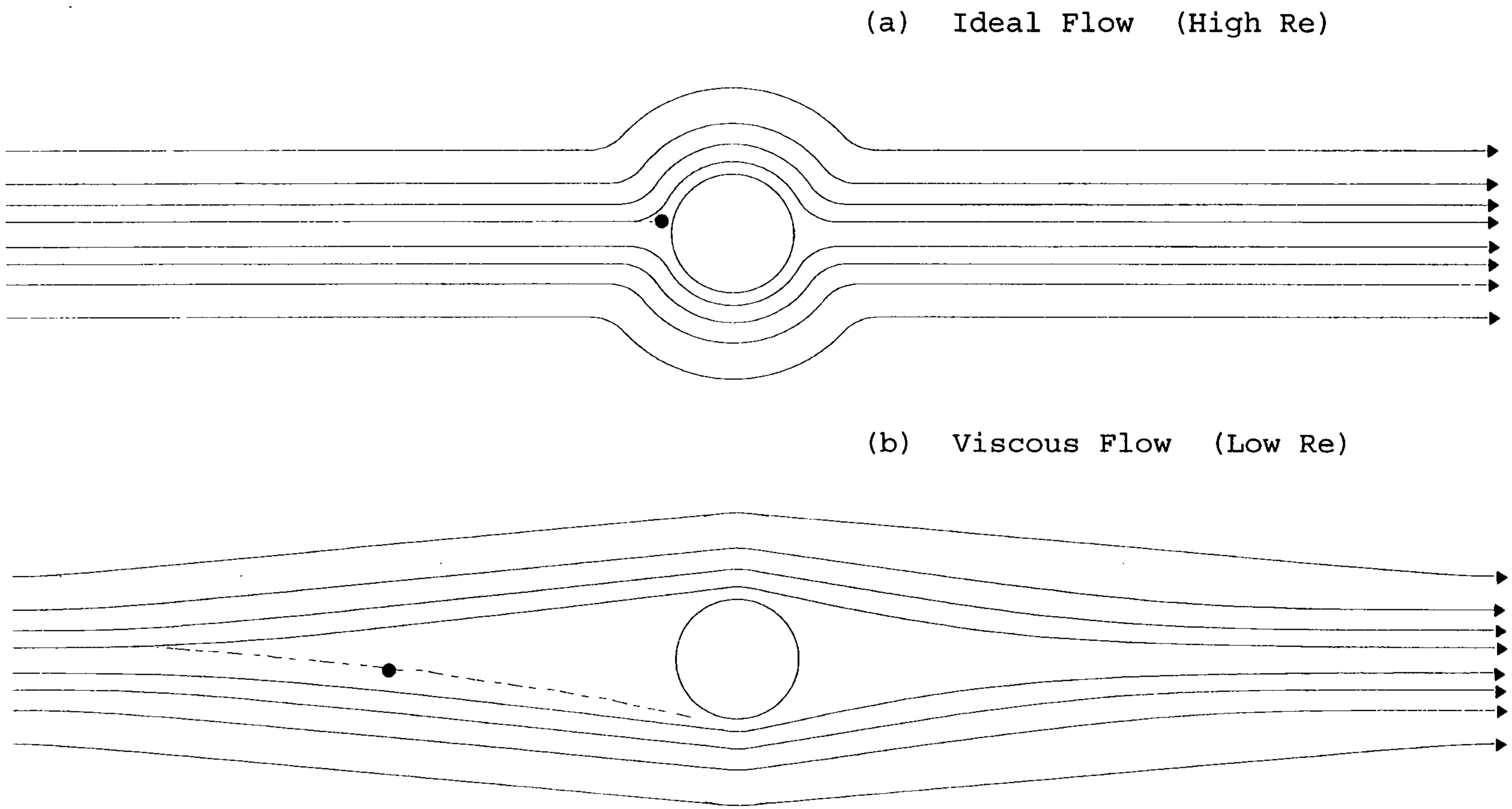

Figure 2-6. Effect of Reynolds Number on Inertial Impaction: (a) Late streamline separation, particle collects; (b) Early streamline separation, particle does not collect

there is practically no fluid disturbance at a distance of two fiber diameters upstream." If this is true, then the more viscous flow will cause the particle to separate from the streamline earlier, and the collector may not meet the stopping distance criteria. Hence the particle may not be collected. In fact Strauss (1966) reports that "the limiting trajectory can be shown to be a function of Reynolds and Stokes numbers only." Figure 2-7 summarizes the results of the various researchers reported on by Strauss. The results plot single fiber impaction efficiency as a function of Stokes number, and the effect of the Reynolds number becomes readily apparent.

Whitby (1965) studied and compared many theories on diffusion, interception, and inertial impaction. Moreover, he reported on a theory which "accurately predicts impaction efficiency for all Reynold's numbers." Whitby's theory is superimposed on the data of Strauss, and can be seen at Re = 0.2 (viscous flow) and at Re = 2000 (potential flow). Since this theory will be used as the foundation of the present study, the mathematics will be reviewed in detail in the following chapter. None-the-less, Whitby's theory relates inertial impaction directly to ψ, the inertial impaction parameter, where ψ has been shown to be a function of Re.

Of all theories reviewed, Whitby's inertial impaction theory does indeed seem to be most accurate up to certain velocities and / or particle sizes. However, he also stated that "all theories overestimate the efficiency for particle diameters greater than about 5 μm, because this is the size at which particles begin to bounce off the fibers at normal filter velocities. Since all of the theories assume that

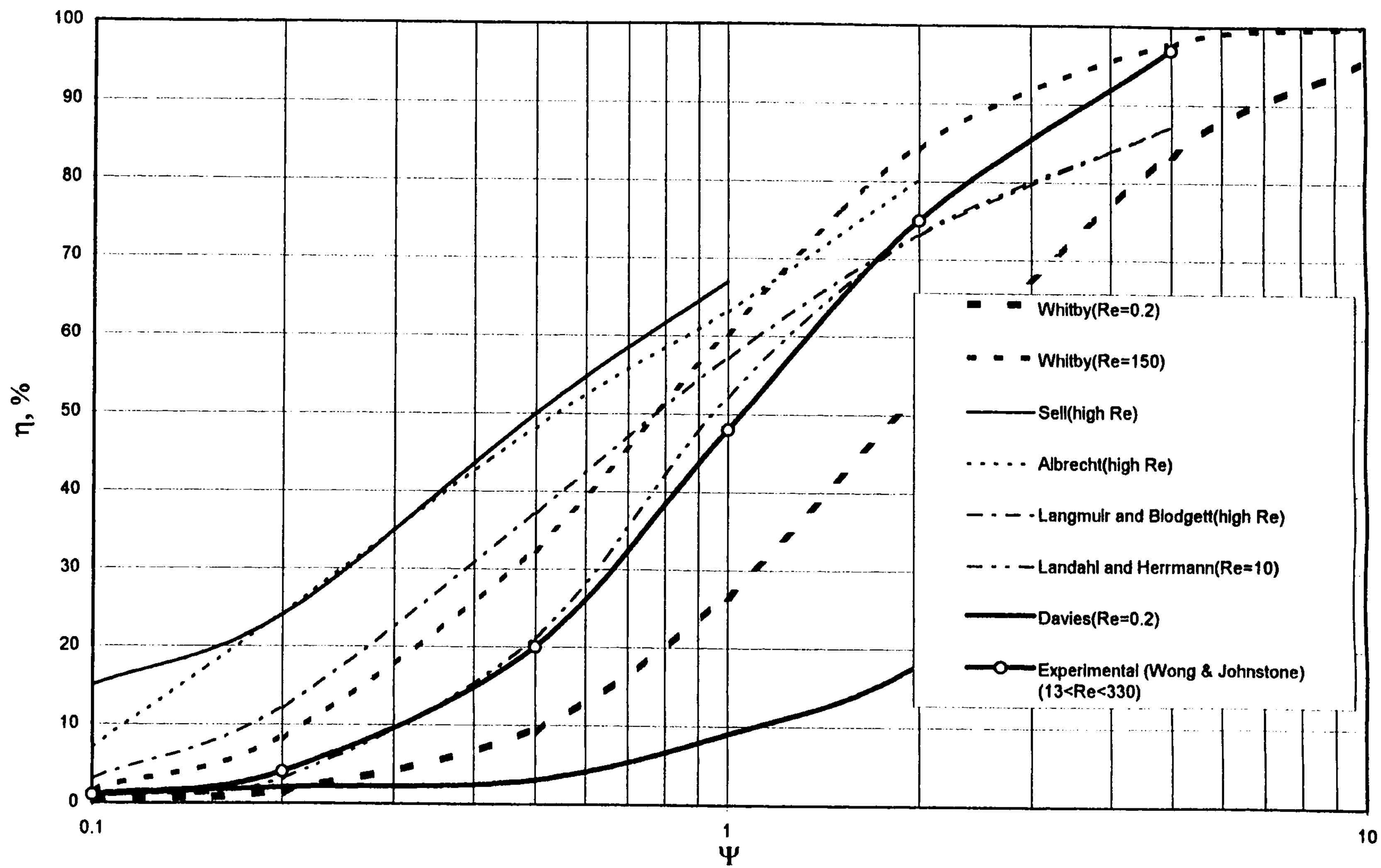

Figure 2-7. Efficiency of Inertial Impaction by Spheres on Cylinders Based on Various Theories (From Strauss, 1966)

particles which strike a fiber stick, this represents a limit above which they should not be applied."

2.6 Particle Adhesion upon Impaction

Already cited above were Davies (1973) and Whitby (1965) as having documented a particle *bounce* or lack of adhesion upon particle-fiber impact at high air flow rates. The purpose of this section is to review all literature to date concerning this subject.

Stenhouse (1972) reported that raising the humidity of the surrounding air also increases adhesion. Jordon (1954) carried out experiments on the velocity of air required to overcome the adhesion of particles of quartz dust and glass which had been allowed to settle upon clean microscope cover glasses. It was shown that air speeds of 100 m/sec were required to disengage only 20% of the particles (Davies, 1973). Loeffler (1974) noted that existing theory merely considered the probability of impact of particles with fibers, and is inadequate in explaining the real efficiencies of collection because particles can rebound after impact. He further concluded that the physical nature of the particles and fibers play an important role in collection efficiencies. Loeffler cites numerous authors: Gillespie (1955), Dorman (1966), Whitby (1965), and Stenhouse (1970) as concluding that "the probability of adhesion is rarely 100% (in inertia dominated systems)."

Loeffler continued to suggest that the retention of particles on fiber surfaces were dependent on the following conditions: (a) The energy of adhesion which must be overcome to detach the particle must be larger than the elastic energy available from the partly elastic and partly inelastic impact; (b) The force of adhesion retaining the particle on the fiber surface must be larger than the separating force exerted on the particle by the gas flow around the fiber.

Stenhouse (1972) also conducted experiments with particle adhesion. He used model filters of layers of regularly spaced stainless steel wires. At higher velocities and with larger particles, adhesion either failed to be established or to be maintained. Davies (1973) reported the literature as being "full of references dealing with the estimation of van der Waals and electrostatic forces of adhesion." He also states that it is "commonly assumed" that the fate of deposited particles is controlled by adhesion forces between the particles and fibers and on the aerodynamic forces acting on the deposited particles. Yet experiments cited in his work show that "particles in the range of 1-3 μm radius are unlikely to be dislodged in any but heavily overblown filters of poor quality, as long as the filter is clean." He further suggests that as the particle size decreases below 1 μm the chance of redispersion becomes even smaller.

Hence, experience suggests that one cause of the penetration of filters is the rebounding of particles. Once a particle has rebounded, it will proceed more slowly to its next encounter with a fiber, and so on, until it collides with insufficient energy to bounce off again and remains attached to the fiber. The chance of penetration will obviously depend on the number of collisions a particle can make as it proceeds through the filter (Davies, 1973). In a very recent article, Hanley et al. (1995) noted "particle bounce as being responsible for a downturn in efficiency as particle diameter increases above about 2 μm" for several of the filters discussed in that article, particularly low efficiency furnace filters.

Dahneke (1971) studied the involvement of small particle dynamics, in particular the rebound of particles upon flat surface impaction. He extended the existing theory for the coefficient of restitution of thin plates to cylinders to represent that of filter fibers. The coefficient of restitution is defined as the ratio of normal particle velocity at the instant of rebound over normal particle velocity at the instant of contact. He noted the most important mechanisms by which energy is lost are (a) plastic deformation; (b) "internal friction" resulting in the generation of heat when a material is subjected to a stress cycle; (c) radiation of compressive, shear, and Rayleigh surface waves (i.e., acoustic waves) into the surface material; and (d) flexural work if the surface is that of a thin (flexible) body.

In both mechanisms (c) and (d), some of the particle's energy is converted to elastic strain and kinetic energy in stress waves generated in the surface material. For mechanism (c), the motion associated with the waves is of very small scale, displacement being only a few atomic diameters. Thus the capacity of this mechanism to dissipate energy is comparatively small. For mechanism (d) however, the wave motion is of a larger scale associated with bulk displacement, i.e., flexing, of the entire body. For sufficiently thin bodies the flexural work contained in this wave can be essentially all of the particle's initial kinetic energy. The author states that the coefficient of restitution for thin body collisions can be accurately calculated. He cites this coefficient for 1.3 μm diameter polystyrene spheres bouncing on a quartz surface in vacuum as being within about 1% of unity for particle velocities of 6, 13, and 24 m/sec.

Although the critical velocities which Dahneke derived "seem impossibly low" (Davies, 1973) for small spheres striking hard, plane surfaces, the researcher did have some interesting suggestions in filter design. He suggested that for maximum capture ability, filters should contain fibers of small diameter made of material with low Young's modulus, which is simply a material property. Such a filter would have the best ability to capture the full range of particle sizes, including the large solid dust particles, which occur in natural aerosols. Filtration efficiency of large solid particles will be maximum at some intermediate velocity where "inertial interception" has been obtained but where bouncing is not yet important. Decrease of fiber diameter thus has a twofold influence on the capture of large particles as it (a) lowers the velocity range in which "inertial interception" is effective; and (b) raises the velocity at which the onset of bouncing occurs. His theory provided no practical information for improving the design of aerosol impactors. However, he did state "the only way to capture solid aerosol particles by impaction is to coat the impaction surface with a viscous liquid. The coating can be applied either beforehand or during the impaction."

Walkenhorst (1972) passed an aerosol, produced by spraying olive oil, through experimental filters before testing them against coal dust (Davies, 1973). This olive oil wetted the surface of the wires and spread over them making a large improvement in adhesion. Filtration efficiencies were improved on several accounts. First in general, and secondly, the efficiencies improved with particle size. However, the efficiencies after the coating of olive oil could not be related to velocity. Davies suggested that cheap filters operating at high air velocities, "several meters per second," could be improved with an application of oil on the fibers. However, an over-application would probably have an adverse effect.

Cheng and Yeh (1979) studied particle bounce in cascade impactors. They reported the results of a semiempirical model that related impact velocity at the inception of bounce, particle diameter, and particle density which they proposed. The impact velocity on the center line of both round jets and rectangular jets was calculated by solving particle motion equations. They reported on experiments which were performed to evaluate the retention efficiency of the sierra radial slit jet impactor using latex particles collected on uncoated stainless steel. The critical value of the product of calculated impact velocity, particle diameter, and square root of specific gravity was found to be between 2.5×10^{-6} and 4.64×10^{-6} m^2/s at the inception of bounce. Values larger than this were reported to predict particle bounce in cascade impactors.

Wang and Walter (1988) discussed the dependence of adhesion on the angle of incidence and the tangential velocity of a particles impacting a cylinder. Their data suggest that the tangential velocity component can cause particle bounce even when the normal component is below the critical velocity. This study found the critical velocity to depend on the particle diameter to the power of -1.29. This is in close agreement with the results of Cheng and Yeh (1979) but does not agree with the flattening theory of Dahneke (1972).

Broom (1979) studied the adhesion of particles in fibrous air filters. Using a fundamental experimental approach the mechanism of non-adhesion which is dominant in the high inertial regime was investigated. High speed films were taken of the impact of monosized glass particles on to the edge of a slowly rotating wheel. The subsequent adhesion probability was calculated from the film using a frame by frame digital analyzer and a digital computer. The adhesion probability and the coefficient of restitution for particles of 4.7 μm, 8.6 μm and 11 μm diameter were determined for two angles of impact over a range of impact velocities. The effect of the surface properties was investigated by studying the impact of particles on wheels machined from differing materials. The adhesion probability in each velocity interval of 0.05 m/s was determined by measuring the ratio of the number of adhering particles to the total number of incident colliding particles. The critical velocity for adhesion was calculated theoretically from an energy balance on the particles. Particles impacting on a surfaces with a velocity greater than the critical velocity will bounce and those colliding at lower velocities will adhere. The adhesion probabilities did not exhibit the same step decrease with increasing impact velocity in this study. This apparent deviation from theory "was not totally unexpected." The researcher stated that "The distribution in the adhesion probability is primarily due to surface micro-aspirates; the microstructure of the colliding surfaces will be different for each collision." The author, as well, concluded with some useful observations about which factors would lead to an increase in the single fiber efficiency in both the "collision controlled," and the "adhesion controlled" regimes. This is taken to mean the "pre-bounce" and "post-bounce" regions of the inertial impaction regime to be developed in detail later in this thesis. Finally the critical velocity was determined which was believed to be more "applicable to practical situations which considered the air drag due to the presence of the fiber," in other words, real (viscous) fluids. The critical velocity was compared to the theories of other researchers and was found to be appreciably higher (see Dahneke, 1971; and Loffler, 1974). These comparisons also concur with the criticisms of Davies (1973), and of another researcher cited in the study of Broom (1979).

Esmen et al. (1978) studied the adhesion of particles upon impaction. This group of researchers followed the work of Dahneke (1971) again using flat-plate impactors. They reported "excellent agreement" with Dahneke's expressions developed for the maximum adhesive force and existing experimental data. However, the comparison was "made by selection of reasonable values for several parameters involved." Since the energy measurements were more sensitive to particle and surface deformation, the objective of their research team was a more rigorous test of the theory by comparing theoretical and experimental values for the maximum adhesive energy. One interesting aspect of their research was the application of a very thin layer of carbon black to the substrate, so that "foot prints" of those particles which hit and bounce would be left behind. The report shows a typical photomicrograph showing collected particles and bounce footprints. The report concluded by stating that the experimental results and the theory suggested by Dahneke (1971) agree well.

Davies (1973) suggests that "the factors which govern the release of deposited particles are only appreciable in rather poor filters which function at high air velocities, say 1 m/sec and over." Davis et al., (1994) studied just such a series of "poor" air filters. These researchers studied the efficiencies of eleven different commercially available HVAC filters to determine removal efficiencies in the particle size range of 0.5 to 4.0 μm and high face velocities. The primary removal mechanism was reported as inertial impaction. Filter efficiencies were compared to theoretical efficiencies where theory was observed to overpredict. It was reported that these less-than-predicted results were probably due to the particle bounce effect.

Ellenbecker, et al. (1980) seems to be the first research team to specifically study impaction and particle bounce in fibrous filters operating at high Stokes numbers. Figure 2-8 shows the theoretical and experimental single fiber impaction efficiencies for various values of Stokes number, for both fly ash and DOP. The DOP was noted to agree nicely with existing inertial impaction theory, yet the fly ash departed from theory at higher Stokes number. These discrepancies prompted the researchers to relate the experimentally measured adhesion probability to particle kinetic energy using a variety of materials(fly ash, NaCl, DOP, uranine) on a variety of collection substrates (steel mesh, polyamide fibers, and flat brass). The adhesion probability can be obtained from experimental data by taking the ratio of the experimentally measured single fiber collection efficiency to the theoretical single fiber collection efficiency. Figure 2-9 shows the results of fly ash adhesion probability vs. particle kinetic energy from that study. Figure 2-10 is a comparison of adhesion probability data with those of other researchers. The authors were able to characterize the kinetic energy regimes where particle adhesion would be predicted to be very good ($E_k < 10^{-15}$ J) and where the lack of particle adhesion can

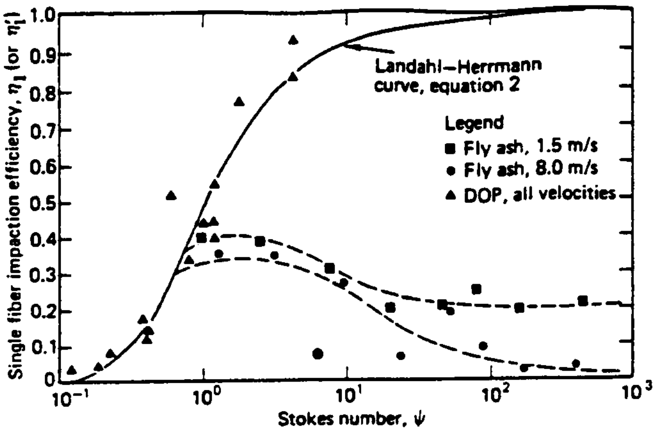

Figure 2-8. Theoretical and Experimental Single Fiber Impaction Efficiencies vs. Stokes Number (From Ellenbecker et al., 1980)

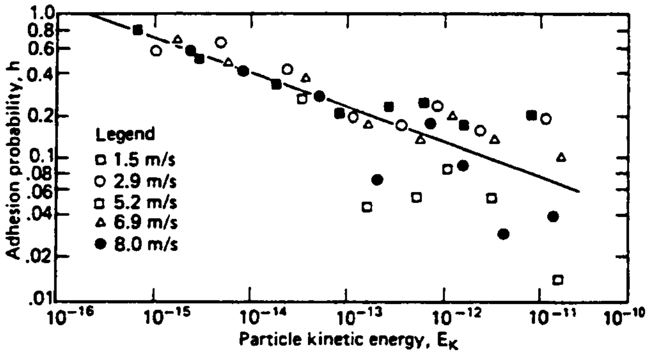

Figure 2-9. Fly Ash Adhesion Probability vs. Particle Kinetic Energy (From Ellenbecker et al., 1980)

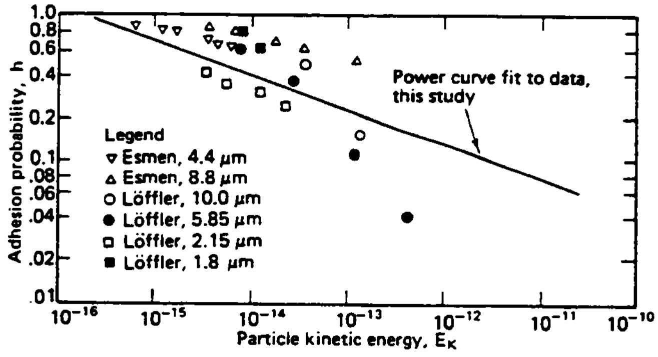

Figure 2-10. Comparison of Adhesion Probability Data with Those of Other Investigators (From Ellenbecker et al., 1980)

dominate fiber collection characteristics ($E_k > 10^{-15}$ J). They also stated that "in all cases, particle adhesion probability may be a strong function of the particular particle and fiber material used." This theory, as well as the data from the study will be presented in more detail in this thesis in a later chapter.

Phillips et al. (1995) presented the results of an investigation to study particle bounce in polypropylene melt-blown media. These media were manufactured at a variety of operating conditions, to produce a medium which might be suitable for use in indoor air quality filters. The filter media were prepared at the Textiles and Nonwovens Development Center (TANDEC) and tested for filtration efficiency in the Air Quality Laboratory housed in the Department of Civil and Environmental Engineering at the University of Tennessee, Knoxville. Efficiencies were determined using both cold, polydispersed dioctylpthalate (DOP), as well as monodispersed polystyrene latex (PSL) particles (0.6 to 3.0 μm) using an ASTM 1215 filtration test stand. The objectives of the research were to determine the efficiency of the media at velocities ranging from 3 to 375 cm/s and to compare the measured results to filtration theory.

The researchers reported that at the higher velocities, typical of those used in indoor air filters, the experimental efficiencies using dry particles were significantly less than both the DOP and theoretical efficiencies due to the kinetic energy of the particles which resulted in particle bounce. As with the Ellenbecker et al. (1980) study, correlation's were developed using particle adhesion as a function of the kinetic energy. The data are consistent with the findings of the Ellenbecker et al. (1980) study. That is to say, these researchers were also able to characterize the kinetic energy regimes where particle adhesion would be predicted to be very good ($E_k < 10^{-15}$ J) and where the lack of particle adhesion can dominate fiber collection characteristics ($E_k > 10^{-15}$ J).

Phillips et al. (1995) also conducted tests on a melt-blown medium which was coated with a tackifier. The results showed that the efficiencies at high velocities were improved due to the reduction in particle bounce, while the efficiencies at low velocities were unchanged even as a result of the larger effective fiber diameters which resulted from application of the tackifier. Lastly, research was conducted to determine the effect of various concentrations of tackifier.

The use of tackifiers were reported to improve the efficiencies of indoor air quality filters operating at high velocities (2 - 4 m/s). This is due to the fact that these velocities impart high kinetic energies to the particles, and this kinetic energy is believed to cause these particles to bounce upon impact with the filter fibers. The tackifier increases adhesion probability upon impact. However, filter efficiency is unimproved at low filtration velocities when add-on tackifier is applied. Hence, a tackifier may not be useful for improvement of filtration efficiency, in those cases where there is already a low facial velocity, such as a pleated media, and where diffusion and interception are the more dominant mechanisms.

Further, the researchers concluded that existing filtration theory tended to agree well with data derived from liquid aerosols such as DOP, but the behavior of dry aerosols, such as PSL microspheres, departs significantly from the theory. This departure by dry particles was typically observed at kinetic energies in excess of 10^{-15} J. However, by using the correlation's of adhesion probability investigated therein, the collection of these solid particles in fibrous media may be correctly predicted.

CHAPTER 3

THEORETICAL MODEL

3.1 Determination of Effective Fiber Diameter

As will be discussed in a later chapter, attempts to use scanning electron microscopy (SEM) to physically measure the filter fiber diameter can be time consuming, and may not represent a true aerodynamic fiber diameter. Other sources (Japuntich, 1991) describe the use of the effective fiber diameter, which may be determined from a pressure drop equation such as the following (Davies, 1973):

$$\Delta P = \frac{16 c \mu_g V L}{K D^2 \varepsilon} \qquad (1)$$

where:

ΔP = pressure drop, N/m^2

c = packing density

μ_g = viscosity, $kg\text{-}s/m^2$

V = face velocity, m/s

L = filter thickness, m

D_f = fiber diameter, m

ε = inhomogeneity factor (usually 1.0 for randomly packed filter)

All of the above parameters are readily measured with the exception of the packing density, c, which can be calculated as

$$c = \frac{W_f}{\rho_f L} \quad (2)$$

The areal density of the filter, W_f, may be determined gravimetrically (kg/m^2). The Kuwabara hydrodynamic factor, K, is defined as

$$K = -\frac{1}{2}\ln c - \frac{3}{4} + c - \frac{c^2}{4} \quad (3)$$

Equation (1) may be rearranged to solve for the effective fiber diameter, D_{eff}, based on the other measurable parameters:

$$D_{eff} = \sqrt{\frac{16c\mu_g VL}{K\Delta P}} \quad (4)$$

The inhomogeneity factor, ε, is assigned a value of 1.0 since the effective fiber diameter is determined from the actual pressure drop. For small values of Reynolds number, Re, the pressure drop, ΔP, across the filter varies linearly with velocity. For the determination of D_{eff}, the experimental velocity-pressure drop profiles were created and recorded for each filter using the ASTM 1215 test stand. A least squares linear regression was then performed for each filter of ΔP versus velocity to arrive at an average value of $\Delta P/V$. This value was then used in Equation (4) to calculate D_{eff}.

3.2 Prediction of Particle Collection Efficiency in Fibrous Air Filters

Davies (1973) reported the particle collection efficiency from air in fibrous filters as being based on a combination of three removal mechanisms: diffusion, interception, and inertial impaction. Figure 2-5 helps the reader to visualize these mechanisms. At low air velocities, diffusion and interception are known to dominate, and at high air velocities inertial impaction is the prevailing particle removal mechanism. The single fiber removal efficiency, η_s, may be approximated as the overall sum of the three efficiencies:

$$\eta_s = \eta_D + \eta_R + \eta_I \qquad (5)$$

where the subscripts D, R, and I represent the efficiencies due to diffusion, interception, and inertial impaction, respectively for a given particle size. The overall efficiency of the filter, η_0, and penetration, Pn_0, for a specific particle size are

$$\begin{aligned} \eta_0 &= 1 - e^{-\eta_s S} \\ Pn_0 &= 1 - \eta_0 = e^{-\eta_s S} \end{aligned} \qquad (6)$$

where S is referred to as the solidarity factor and is defined as follows

$$S = \frac{4cL}{\pi D_{eff}} \qquad (7)$$

For the single fiber collection efficiencies governed by interception and diffusion respectively, Liu and Rubow (1986) showed that

$$\eta_R = \frac{1}{\varepsilon} \frac{(1 - c)}{K} \frac{R^2}{(1 + R)} \qquad (8)$$

and

$$\eta_D = \frac{2.58}{\varepsilon} \frac{(1 - c)^{1/3}}{K} P_e^{-2/3} \qquad (9)$$

where ε is again taken to be 1.0 since an effective fiber diameter is used in the model. The term P_e is the Peclet number defined as

$$P_e = \frac{V D_f}{\mathscr{D}} \qquad (10)$$

and R is the interception parameter defined as

$$R = \frac{D_p}{D_f} \qquad (11)$$

D_p is the particle diameter and D_f is the fiber diameter. In this case the effective fiber diameter, D_{eff}, was used. The parameter, $\mathscr{D}$, is the particle diffusivity (m^2/s) defined as

$$\mathscr{D} = \frac{1.38 \times 10^{-23} K_c T}{3\pi\mu_g D_p} \qquad (12)$$

where

Kc = Cunningham's Correction Factor

T = Absolute Temperature (°K)

Liu and Rubow (1986) recommended that the above equations be used for low velocities and particles sizes where interception and diffusion are thought to be prevalent. The specific ranges reported were particle diameters of 0.034 - 1.3 µm and velocities of 0.01 - 0.3 m/s.

At higher velocities and particles sizes where inertial impaction is the prevailing collection mechanism, various researchers have developed theoretical and/or empirical relationships relating the single fiber impaction efficiency, η_I, to Stokes' number at different flow regimes (Strauss, 1966). Stokes' number, ψ, which is also known as the inertial impaction parameter is defined as

$$\psi = \frac{\rho_p D_p^2 V K_c}{18 \mu_g D_{eff}} \qquad (13)$$

where ρ_p is the particle density (kg/m^3).

In the present study the approach developed by Whitby (1965) was used to determine the single fiber collection efficiency. Whitby was able to express the inertial impaction parameter, ψ, as a function of Reynold's number, for $0.2 < Re < 150$, using the following relationship:

$$\psi_M = 1.57\, Re^{-0.137} \qquad (14)$$

The value of ψ_M is the value of the inertial impaction parameter which yields a fractional single fiber collection efficiency of 0.5. The value of the geometric standard deviation, σ, was reported by Whitby to have a value of 1.65. For Reynolds numbers, Re, less than 0.2, the value of ψ_M was reported to be 1.96. Whitby described a graphical technique to determine the single fiber inertial impaction efficiency, η_I, by constructing a linear graph on log probability paper using $\psi_M^{0.5}$ from equation 14. The value of $\psi_M^{0.5}$ is plotted at the 50th percentile, and the value 1.65$\times$ $\psi_M^{0.5}$ is plotted at the 84.15th percentile, after which a linear curve is constructed using these two values. Once the graph is constructed, and the square root of the value of ψ is calculated, the efficiency, η_I, can be read from the probability scale in percent.

Davis (1994) simplified Whitby's graphical procedure by observing that the equation which plots as a straight line on log-probability paper, and relates the single fiber impaction efficiency, η_I, directly to the inertial impaction parameter, ψ, for any Re is

$$\eta_I = 0.5 + 0.5\,\mathrm{erf}\left[\frac{\ln\left(\frac{\psi}{\psi_M}\right)^{0.5}}{\sqrt{2}\ln\sigma}\right] \tag{15}$$

In the previous chapter, Figure 2-6 showed how this theory described inertial impaction efficiency for all Re.

CHAPTER 4

MATERIALS AND METHODS

4.1 Filtration Test Stand

4.1.1 Overview

The filtration test stand used in this research conforms to the ASTM F 1215-89 test stand reported on and described in previous literature (Davis, 1994). ASTM F 1215-89 describes the Standard Test Method for Determining the Initial Efficiency of a Flatsheet Filter Medium in an Airflow Using Latex Spheres. The method employs monodispersed polystyrene latex spheres in the range of 0.5 to 5.0 µm at airflow velocities of 1-25 cm/s for flatsheet filter media. Monodispersed is defined as a particle size distribution having a geometric standard deviation (GSD) of less than 1.25 (Japuntich, 1991). The standard method applies to efficiencies of less than 99.9% or penetrations of greater than 0.001 at 1.0 µm.

The method is established to determine the initial efficiency of a flatsheet filter medium by sampling representative volumes of air containing a latex aerosol concentration upstream and downstream from a filter medium. In this technique, there is no need to test isokinetically, since there is no requirement that the sampled mass aerosol concentrations be absolute. It is only necessary to sample relative mass aerosol concentrations upstream and downstream. Since sample volumes are extracted both upstream and downstream of the filter sample, any oversampling or undersampling error is canceled, yielding an accurate value of filter penetration at that velocity.

The Test Stand reported on by Davis (1994) was modified to provide higher flow capacity in order to simulate air flows resident in HVAC systems. Figure 4-1 shows a schematic of the test stand. The apparatus is basically an air handling system which consists of an air intake, duct work to channel the air, a filter test chamber where the air actually crosses the filter, a regenerative blower to pull the air through the system from the intake, and an air exhaust.

Concurrently in operation is the particle or aerosol generation system. This consists of pressurized air from building supply, a pressure regulator valve, an air desiccator, a filter, an aerosol generator, or atomizer, a mixing chamber, and a charge neutralizer. Filtered and dried air passes through an atomizer containing a hydrosol of monodispersed polystyrene latex spheres in distilled, deionized water. This produces an atomized aerosol containing suspended droplets. The aerosol then passes through a charge neutralizer, and then mixes with preconditioned, HEPA filtered air to produce a stable, neutralized, and dried aerosol of polystyrene (PSL) latex spheres for the efficiency test.

Not to be excluded from this apparatus' description is the seemingly complex array of valves and gages. It should be remembered, however, that the sole function of these instruments is the control & metering of airflow from the intakes to the exhaust.

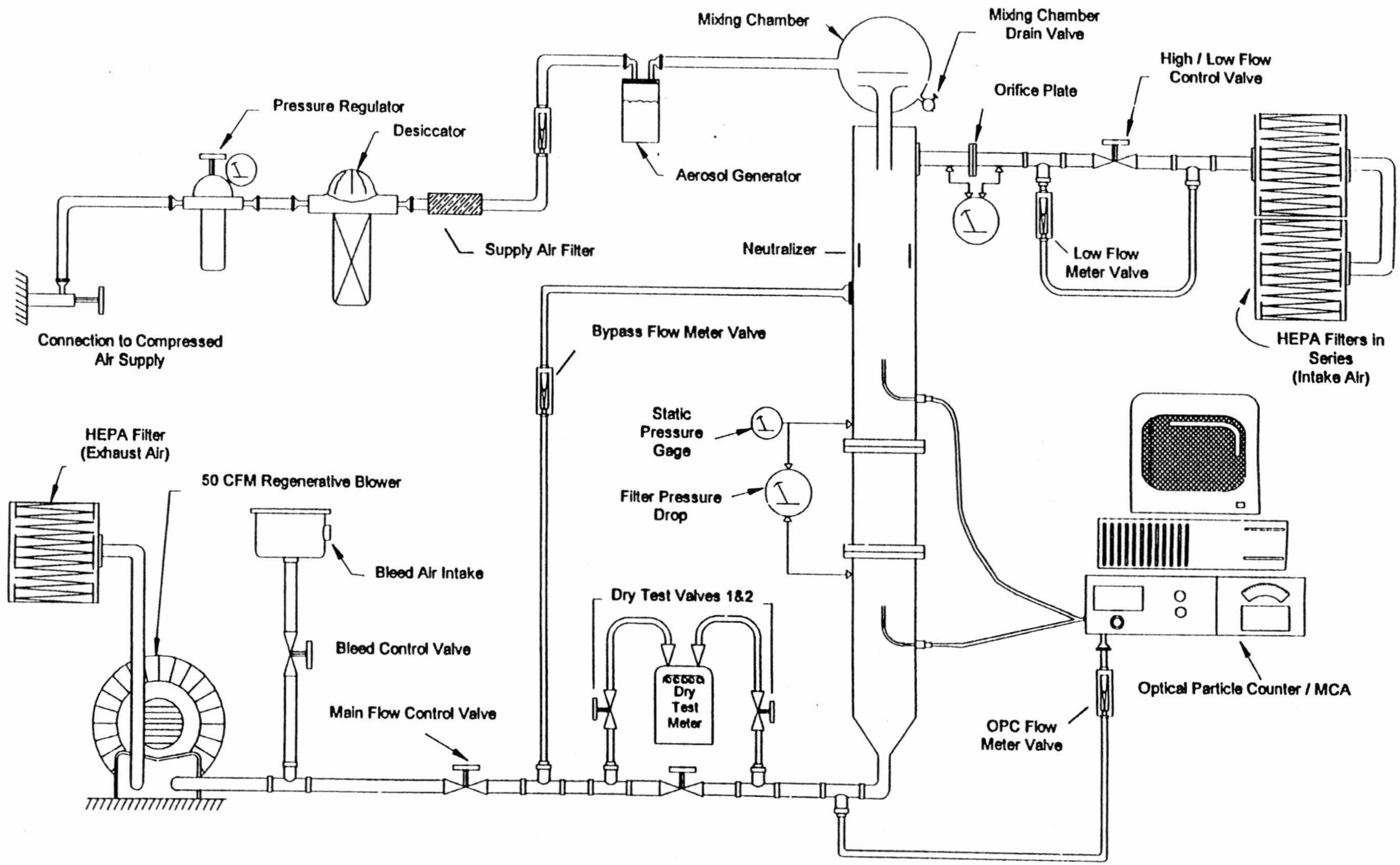

Figure 4-1. Schematic of Indoor Air Quality Filtration Test Stand

4.1.2 Low Flow System

The operation of the system at low flow rates is perhaps the easiest to comprehend since the air is physically metered though a flow control valve (sometimes known as a rotameter). Note in the diagram, that after the air is metered through the flow control valve, it will still pass through the orifice, and register a corresponding pressure drop. However, the pressure drop will be almost immeasurable at this flow rate, and therefore impractical for metering purposes. It is evident during operation why the rotameters are preferred at this flow.

4.1.3 High Flow System

Indoor air velocities across HVAC filters typically range from 1 - 2 m/s (200 - 400 fpm). As flow through constricted tubing, valves, and rotameters in the previous test stand caused excessive pressure drop for these velocities, a more effective system had to be designed to deliver and meter the air flow. Essentially, the ductwork diameters going to and from the test stand were enlarged, and the original vacuum pump was replaced with a 1.5 m^3/min (53 cfm) regenerative blower. The filter test stand and filter holder remained unchanged with a filter medium test diameter of 10.16 cm (4 in).

In order to calibrate the flow, it was decided to employ an orifice plate due to its simplicity of design and operation. In principle, when air passes through a constricted orifice, this constriction causes a pressure drop proportional to the rate of flow. Further, the flow varies linearly when plotted against the square root of the pressure drop across the orifice. This plate was designed to provide a pressure drop of 1 inch of H_2O at a flow of approximately 0.5 m^3/min (18 cfm). The orifice diameter was determined to be 3.15 cm (1.24 in).

Once the orifice meter assembly had been installed, it was necessary to calibrate it to flow conditions. In this case, the dry test meter would have been prohibitive due to excessive flow constriction, so a velocity traverse technique was employed. Velocity traverse sampling ports were located between the main dry test meter valve and the main flow control valve. Two 90° traverses were conducted at a series of flow-rate conditions using a hot wire anemometer at six different locations in each sampling port. Thus for each flow-rate chosen, 12 different velocities were measured. The average of the 12 was then taken for the representative velocity, from which the flow-rate was calibrated.

A plot of the square root of the orifice plate pressure drop versus average velocity yielded a linear calibration curve. This curve was then used to set the filtration test stand at any pre-determined flow-rate.

4.1.4 Operation During Bypass Mode

Without sufficient dilution air, the test aerosols will not become monodispersed. Experience has shown that velocities below 10 centimeters per second (cm/sec), as measured in the 4 inch (id) test chamber, will not provide sufficient dilution air for particle drying before their concentrations are measured in the OPC. This is due to the total flow rate throughout the filter approaching that of the atomizer.

The bypass mode was designed to compensate for this lack of dilution air. A 100 scfh rotameter has been installed to meter in a large quantity of bypass air which provides for sufficient drying. The bypass air is then routed past the test chamber so that the proper velocity of air may still be achieved across the filter. ASTM F 1215-89 specifies a humidity range of 30% to 50% to ensure complete drying.

4.2 Description of Particle Counter, Multi-Channel Analyzer, and Particle Atomization

After establishment of a stable aerosol, a single particle light scattering counter measures the concentration of the particles upstream and downstream from the medium. Davis (1994) also presents a very detailed description of the particle analyzer, which is the same equipment employed in this study. The particle counter is a commercially available Climet Model 208 optical particle counter (OPC) capable of measuring particle sizes of 0.5 to 10.0 µm in diameter. Each particle which passes through the counter scatters light at an intensity related to its size. An amplified intensity creates a voltage pulse of approximately 50 mV - 10 V for particle sizes of 0.5 µm - 10 µm, respectively. As with many commercially available counters, it measures particles greater than one of 5 preset sizes ranging from 0.5 µm to 5 µm. The counter used in this study can measure particle counts in 8 size ranges from 0.5 µm to 10.0 µm. ASTM F 1215-89 requires the use of multiple channels to assure that the distribution is nearly monodispersed.

The method also specifies that the "OPC channels used for counting upstream or downstream aerosols must for any given size particle include the counts in the maximum channel plus counts in all channels on either side of the maximum count channel that produce a count of 50% of the maximum channel count or greater." There must also be a minimum channel separation in the OPC between any residue particle distribution and the latex particle distribution in the test aerosol. Davis (1994) states that with only eight channels of resolution available on the OPC, it is common that nearly all the counts would lie within one to two channels for a "nearly" monodispersed distribution.

The OPC alone meets the requirements of the method, however, a multi-channel analyzer (MCA) with much higher resolution than eight channels significantly enhances the utility of the method. Therefore the counter is used in tandem with a commercially available MCA card which is installed in a standard personal computer. This combination provides 1028 channels of resolution in the 0 - 8 V range for the purpose of particle analysis. The card, a Nucleus Personal Computer Analyzer card (PCA-II) (Oxford Instruments, Oak Ridge, TN) was mounted in an IBM compatible 386SX personal computer.

MCA channels were determined and set for the monodispersed particle sizes of 0.6, 1,2, and 3 μm to be used in this study. These channel widths were identified by atomizing a solution of monodispersed latex spheres using a TSI single jet atomizer followed by drying the droplets and leaving the suspended latex spheres. The spheres served as the particles to be filtered as well as for calibration of the counter. In the case of the DOP, the same atomizer was used to atomize cold DOP. The atomizer created a distribution of DOP droplets which were then sampled using the OPC. Atomizer supply air was typically controlled at 6.5 scfh and not to exceed 15 psig for the PSL spheres. For the DOP, atomizer supply air was varied between 2.5 to 7.0 scfh and again, did not exceed 15 psig. Low atomizer flow generally caused unstable aerosol generation, while high supply flow would cause rapid build-up of DOP onto the filter medium. This build-up would cause undesirable pressure drop rise and, hence, was avoided.

In order to avoid unwanted electrostatic effects, electrical charges on the aerosols were neutralized by exposing the aerosols to a cloud of bipolar ions produced by a radioactive source. Three Static-Master® anti-static devices were placed well upstream of the filter holder. These devices are commercially available from most any photographic products supplier. Each Static-Master® contains a radioactive source of ^{85}krypton which, in conjunction with the other two sources, is able to bring the aerosols to a state of Boltzmann charge equilibrium.

4.3 Manufacture of Research Filter Media

The 50.8 cm wide Melt-blown Line at the University of Tennessee in Knoxville was used to make the filter media used in this study. It features a 4.44 cm extruder, a 50 cm wide die, an electric furnace for heating air, and an Ingersoll-Rand 18.4 m^3/min (650 cfm) air compressor. The process conditions are monitored and controlled by a Barber-Colman Maco V microprocessor. Both the collector support frame and winder are mounted on parallel rails to ensure proper alignment. A scale attached to both rails and pointers on each side of the collector frame enables the accurate and easy setting of die-to-collector distance. Figure 4-2 shows a schematic of the Melt-Blown Pilot Line at the University of Tennessee. A homopolymer polypropylene with a melt flow rate(MFR) of 1200 was used for the media in

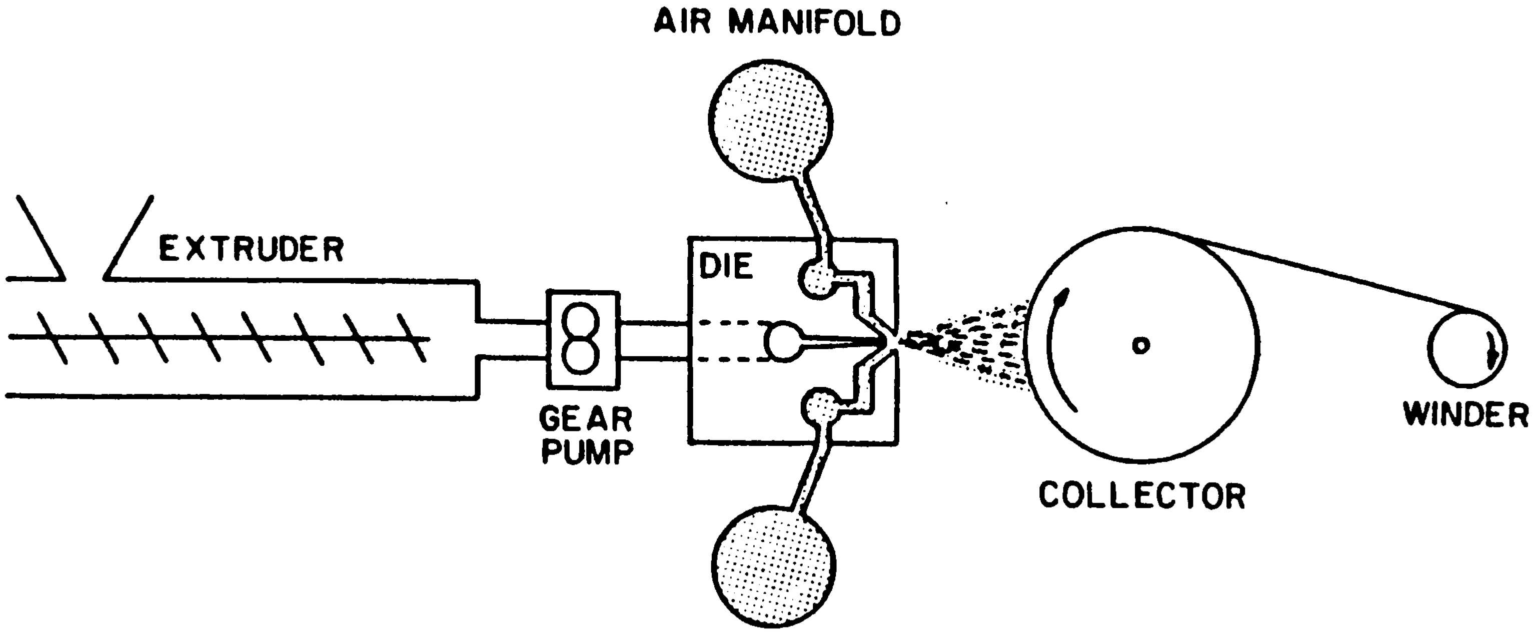

Figure 4-2 Melt-Blown Pilot Line at The University of Tennessee (From Wadsworth and Muschelewicz, 1987)

this study, and was donated by the Exxon Chemical Company in Baytown, Texas.

A series of 26 different filter media were manufactured on the Melt-blown Line. These filters were produced at a full range of operating parameters in the interest of developing a variety of high efficiency air filtration media. The 26 filters were challenged in the test stand primarily using 1 μm latex spheres with filter face velocities of 3 to 300 cm/s. Experimental efficiencies vs. velocity were plotted and evaluated for each filter. Table 1 shows the physical characteristics of the filter medium chosen for this study to investigate particle bounce and the effect of adding a tackifier. The filter medium was manufactured at a take-up rate of 20 fpm and a drum-to-collector distance of 12 inches. The process was operated at 45% air with all other manufacturing parameters being standard for the line.

4.3 Determination of Measured Fiber Diameter

Since melt-blown fibers tend to be heterogeneous in diameter, Table 1 describes two different fiber diameters: the measured fiber diameter, and the effective fiber diameter. The effective fiber diameter was previously described. The measured fiber diameter was determined using an ETEC Auto-Scan (Hayward, CA) scanning electron microscope (SEM), and is the average of 61 fibers counted in 3 separate photomicrographs of one specimen of the melt-blown medium. The specimen was sputter coated for two minutes with gold using a Technics Hummer II (Alexandria, VA). The temperature rise during sputter coating was less than 10 °C. Silver paint was used to ground the edges of the material to the stub to reduce charging during SEM evaluation. Three photomicrographs were taken. A line was drawn on each photomicrograph from opposite corners resulting in a large "X". Fiber diameters of fibers that the "X" intersected were measured. The average fiber diameter was determined.

A comparison was made between effective fiber diameter, D_{eff}, and mean measured fiber diameter. For the 26 filters, measured diameters ranged from approximately 3.5 to 6 µm, whereas effective fiber diameters using equation (4) ranged from approximately 6.5 to 10 µm indicating that, on the average, there was approximately a factor of 2 difference between the effective and the mean measured diameter. Based on these values the filter medium used in this study, and described in Table 1, is typical of the melt-blown media which were produced. As was stated earlier, the effective fiber diameter was used in the theoretical model, rather than the SEM measured values.

Table 1: Properties of Filter Medium Control Sample Used in This Study

Measured Fiber Diameter Average in 1 Control Sample, µm	6.0
Effective Fiber Diameter, µm	7.3
Fiber Density, g/cm^3	0.91
Filter Thickness, mm	1.05
Packing Density	0.0778
Areal Density, g/cm^2	0.0074

4.4 Application of Filter Tackifier Adhesive

The purpose of this phase of the investigation was to evaluate the effectiveness of topical application of a commercially available tackifier as a function of quantity of tackifier applied. The tackifier chosen was provided by

AAF International, Inc., in Louisville, Kentucky, and carries the commercial name of AAF Spray Tack. The tackifier characteristics are proprietary and are, therefore unavailable. The only known characteristics are that it is a "polymer based system, which is water soluble, and completely biodegradable."

To apply the tackifier, eight-inch circles of polypropylene melt blown air filter media were cut and weighed. The samples were held under the surface of the tackifier for 60 seconds and air-dried overnight on wax paper. The tackifier solution concentration was full strength, as supplied by the manufacturer. The treated samples were weighed. Tackifier "add-on" was reported as a percentage of the untreated filter weight. In other words, the difference of the weights of the treated sample minus the untreated sample was determined. This difference was divided by the untreated sample weight and then multiplied times 100. The product was reported as the tackifier add-on in g Tackifier / 100 g Untreated Filter.

4.5 Description of Filter Media Photomicrographs

Photomicrographs of both treated and untreated filter media are shown in the Appendix. The untreated medium shows the heterogeneity of polypropylene melt-blown fibers. The photomicrograph of the treated medium does not reveal tackifier coating, yet one may observe PSL Spheres which had been collected on the medium. The PSL Spheres appear to be about 3 µm in diameter.

CHAPTER 5

RESULTS

A computer model was employed using the Liu, *et al.* (1986) theory for diffusion and interception, and the Whitby (1965) theory for impaction as outlined earlier. The inputs into the model were the effective fiber diameter, media thickness, specimen weight (based on a surface area of 0.0081 m^2), particle density, particle diameter and operating temperature. These inputs were then used to predict the filter efficiencies which were then compared to the experimental efficiencies.

Figure 5-1 shows particle penetration ($1 - \eta_0$) vs. velocity for particle sizes of 0.6, 1, 2, and 3 µm with velocities ranging from 3 to 350 cm/s for the control filter described in Table 1. Both monodispersed latex spheres as well as polydispersed cold DOP were tested for comparison against theory. The data for both types of 0.6 µm particles behaved similarly to the theory in concept. Like theory, both showed a decreasing penetration (or increasing efficiency) with increased velocity as shown in Figure 5-1. However, unlike DOP, the latex spheres diverged from theory at the higher velocities. The 1, 2, and 3 µm PSL spheres results departed from theory at progressively earlier points along the velocity profile, respectively, as the particle size was increased. The 2 and 3 µm PSL spheres data showed a graphic departure from the predicted penetration, with experimental penetrations increasing significantly as velocity increased, while theory predicted a marked decrease in penetration. These departures from theory occurred for

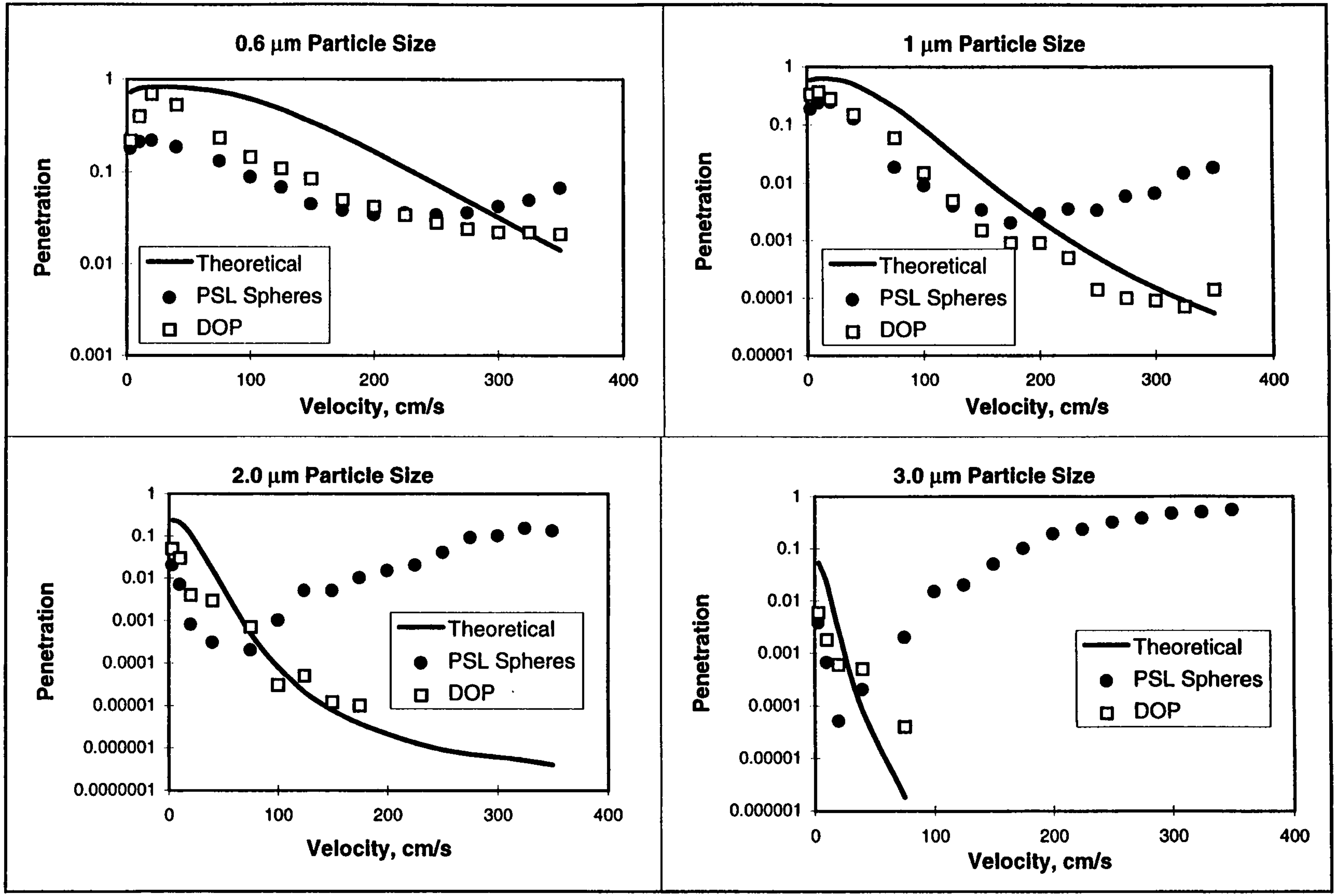

Figure 5-1. ***Experimental vs. Predicted Penetration Using Both Polystyrene Latex Spheres and Dioctylphthalate***

higher velocities as well as larger particle sizes. This suggests a correlation with particle kinetic energy, and gives rise to the hypothesis that particles may be bouncing at higher energies.

The results of the penetration tests using cold DOP in Figure 5-1 tended to agree better with theory than the PSL spheres, as was expected since the DOP has an oily, sticky character which would minimize any bouncing. For this filter medium, DOP particle sizes of 2 and 3 μm tended to agree reasonably well with theory. For the 3 μm DOP data observations were only able to be made at 3 to 75 cm/sec. For velocities greater than 75 cm/s, the efficiencies were so high that it was not possible to atomize enough particles upstream to accurately measure the actual outlet concentration.

One observation from Figure 5-1 is that existing air filtration theory is generally based on liquid aerosol (DOP) removal, and does not accurately predict removal efficiencies of solid, dry aerosols such as PSL spheres.

As a result of the low efficiencies obtained on dry particles at high velocities, it was desired to investigate the effectiveness of the topical application of tackifier to improve filtration efficiencies. Figure 5-2 shows laboratory results of 1 μm PSL particles being filtered at a velocity of 40 cm/s. This corresponds to a relatively low kinetic energy of 4.4E-17 J. The figure shows data from 18 different filters: 4 controls and 14 samples treated with various concentrations of tackifier. Efficiencies for the untreated controls at these conditions typically ranged from 80 to 90%. It can be seen that for all tackifier concentrations, i.e., from a quantity that was undetectable

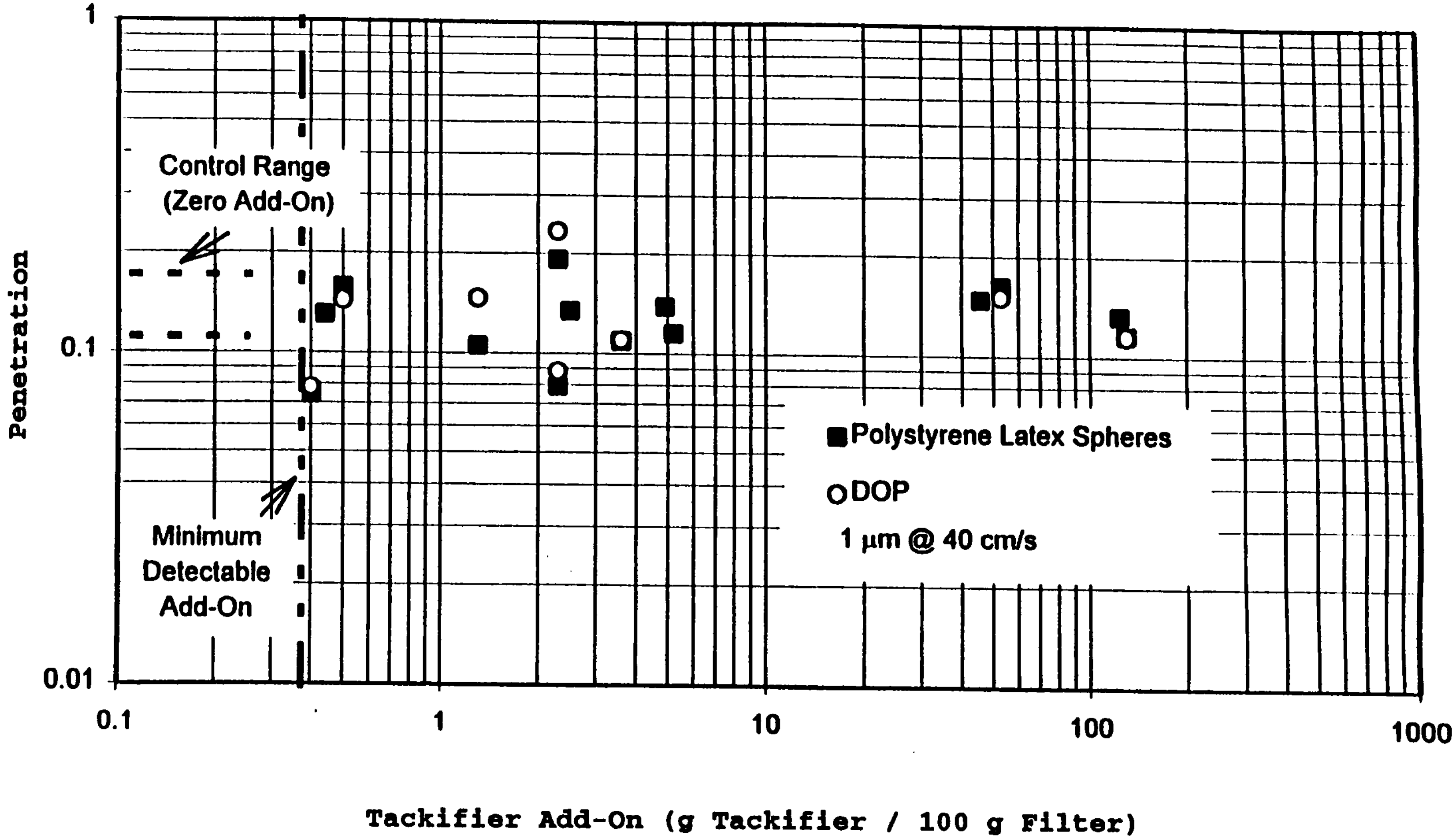

Figure 5-2. Penetration vs. Tackifier Add-On (Ek = 4.4E-17J)

gravimetrically to an add-on of 140 g tackifier / 100 g filter, there was no significant increase nor decrease in filter penetration. The DOP data agreed with the PSL data at this low kinetic energy condition indicating that there was no significant particle bounce.

These initial conditions were chosen since they are known to be dominated by the collection mechanisms of diffusion and interception, and it was desired to investigate the effects on the efficiencies at these conditions as tackifier add-on was increased. Clearly one would expect an increase in filter fiber diameter as add-on is increased, and theory would predict a lower efficiency as fiber diameter is increased. Since penetration is unchanged for all add-on values at these conditions rather than decreasing (due to increased fiber diameter), it was concluded that the tackifier had a slight positive impact on filtration performance. Further, the agreement of the DOP and PSL data suggested a lack of particle bounce at the lower kinetic energies.

Figures 5-3 and 5-4 show penetration vs. tackifier add-on for kinetic energies of 4.17E-15 J and 6.68E-14 J which correspond to PSL spheres of 3 µm and velocities of 75 cm/sec and 300 cm/sec respectively. These conditions were chosen since the corresponding collection mechanism was known to be inertial impaction. In theory the diffusion and interception mechanisms contribute less than 1% of the overall filtration efficiency at these conditions. Moreover, Figure 5-1 suggests that particle bounce is beginning to occur at 75 cm/sec for 3 µm solid particles, and it was desired to investigate the effects of the tackifier at these conditions.

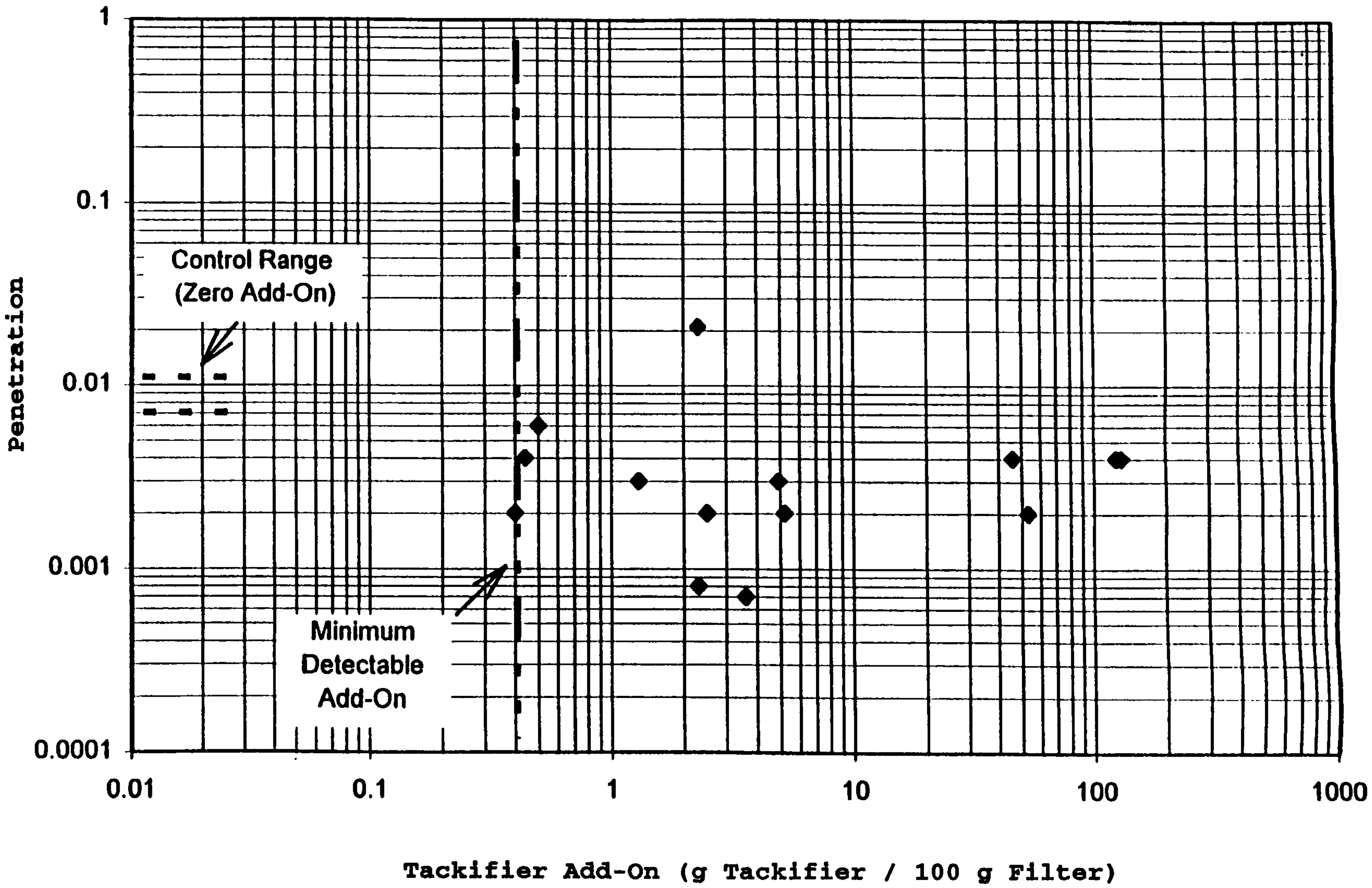

Figure 5-3. Penetration vs. Tackifier Add-On (Ek = 4.17E-15J)

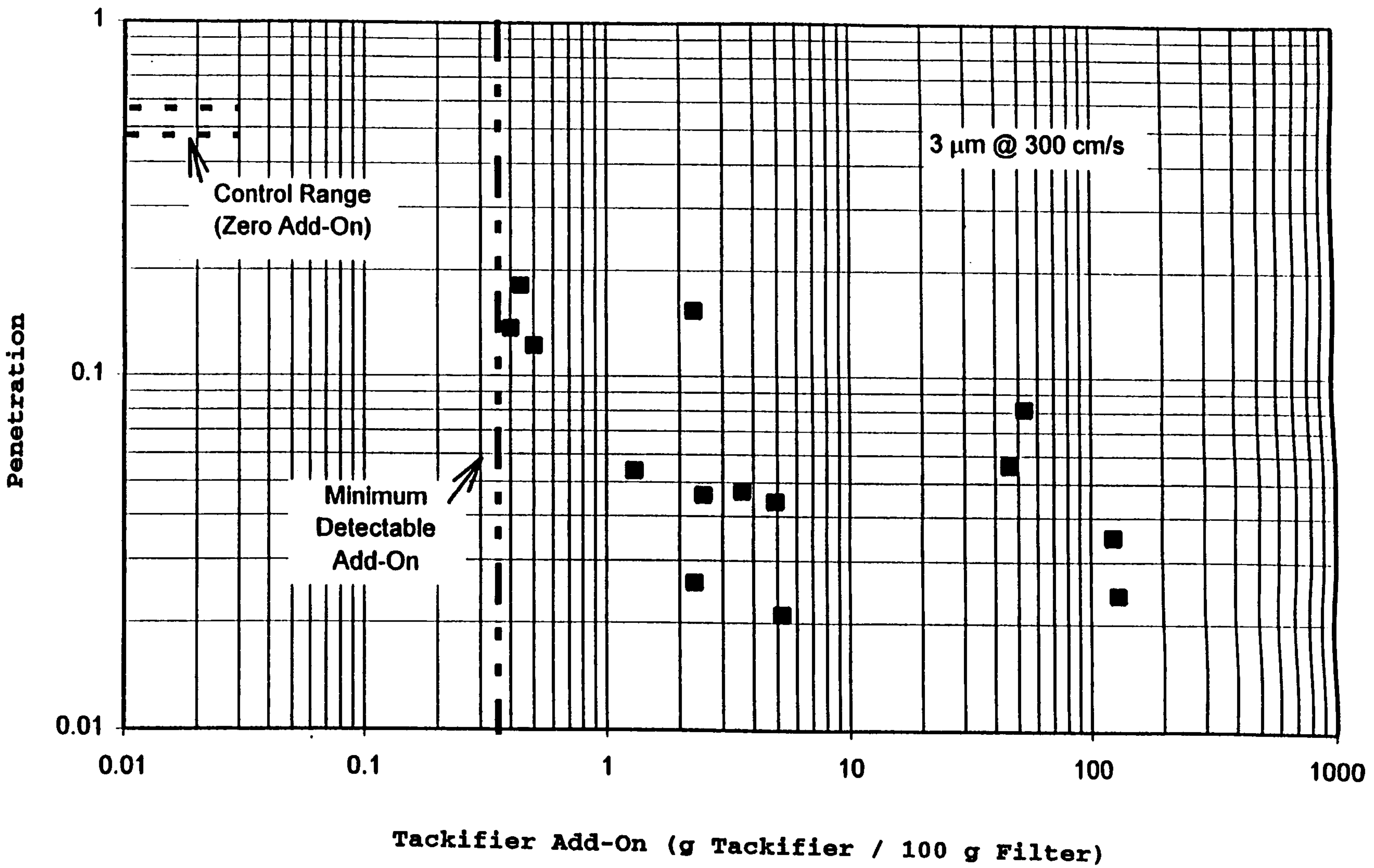

Figure 5-4. Penetration vs. Tackifier Add-On (Ek = 6.68E-14J)

Again, Figures 5-3 and 5-4 show the results of 18 filter samples: 4 controls and 14 samples treated with the tackifier. In the case of Figure 5-3, the efficiencies of the controls ranged from 98.8 to 99.3% on 3 μm particles. After addition of 2-3 g tackifier / 100 g filter, the efficiencies increased to an average of 99.7%

Figure 5-4 shows a more dramatic effect. The controls were much less efficient for 3 μm at 300 cm/sec. Efficiencies ranged from 41.8 to 51.9% efficient, whereas theory would have predicted 99.99999% efficiency. It should be noted also that DOP tests showed efficiencies which were at least 99.9998% for the entire range of add-on values in Figure 5-4. Again it was not possible to determine the exact DOP efficiency since insufficient particle counts were available upstream of the filter to measure such a high efficiency downstream. In theory, as the add-on increased, the fiber diameter would increase causing the filter efficiency to decrease, neglecting the effect of tackiness. Nonetheless, it was impossible to obtain an accurate experimental curve for DOP. However, the disagreement between PSL, DOP and theory again supports the hypothesis of the solid particles bouncing upon fiber impact. When tackifier is added at these conditions, a marked effect is observed. Efficiencies are increased to approximately 96% after addition of 2-3 g tackifier /100 g filter. From the data in Figures 5-2 through 5-4, it would appear that an appropriate amount of tackifier would be 2-3 g tackifier / 100 g filter, since greater values of tackifier add-on did not increase the efficiency.

Figure 5-5 shows the relationship between effective fiber diameter and tackifier addition. Since fiber diameter growth is due to a topical application of tackifier, one

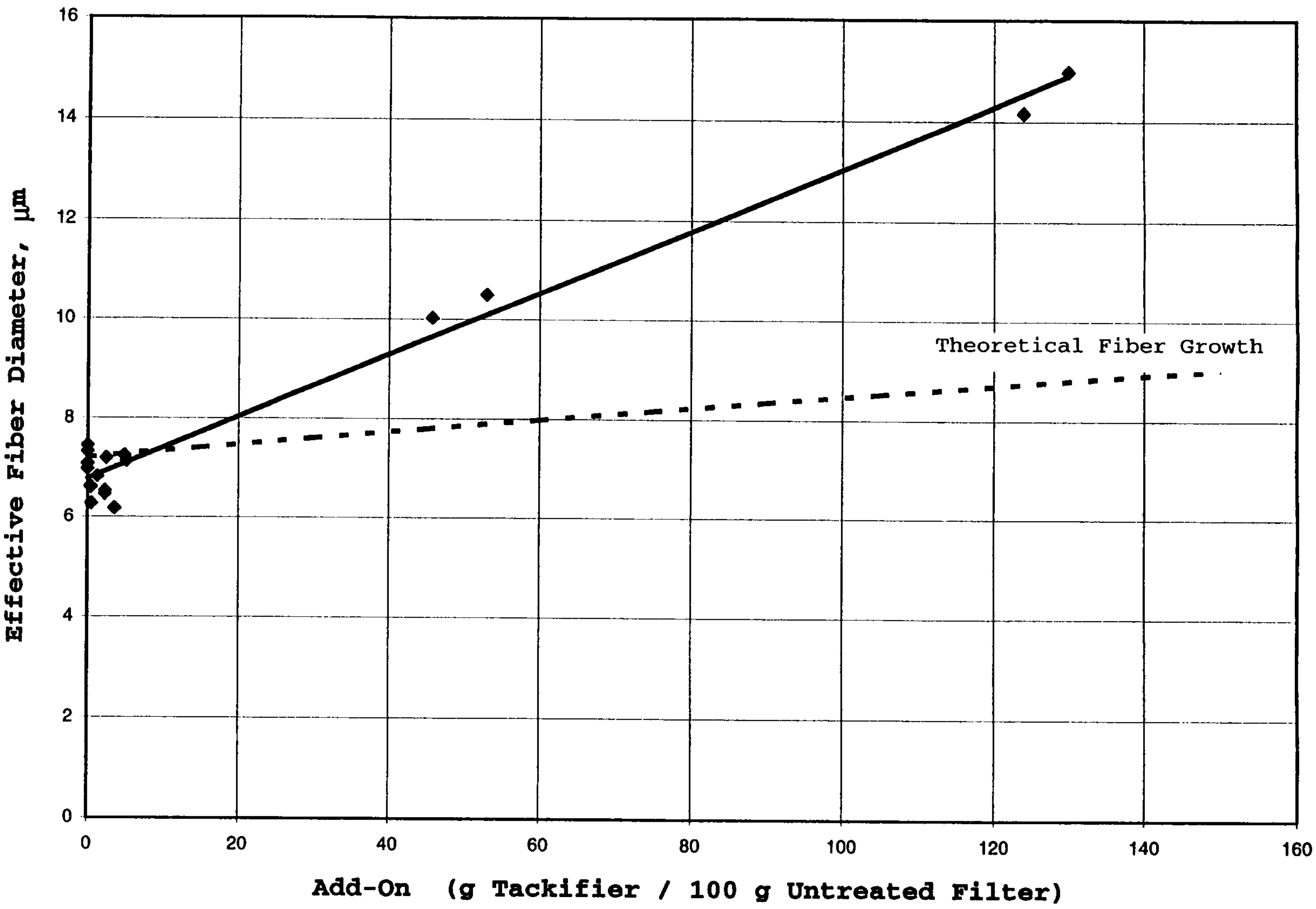

Figure 5-5. Tackifier Add-On vs. Filter Effective Fiber Diameter

would expect a quadratic relationship between the effective fiber diameter and tackifier add-on. This assumes that the mass added is uniformly distributed onto the surface area of the fibers (cylinders). In order to check this assumption a graph was plotted of the change in effective fiber diameter as a function of the amount of tackifier that was topically applied. The effective fiber diameter, D_{eff} was determined as previously described and is an aerodynamically "effective" fiber diameter, not a physically measured diameter. The relationship shows an increase in effective fiber diameter as tackifier add-on was increased. The relationship may indeed be quadratic, but appears linear at least over the observed scale. For comparison purposes, a theoretical fiber diameter growth curve is also shown assuming that the physical growth occurred on each fiber in a uniform manner. In the latter case, the initial fiber diameter was assumed to be the average D_{eff} of the four control filter samples. The theoretical growth curve again appears linear over the observed scale. The difference between the observed fiber growth, and the theoretical growth might be explained by the aerodynamic character of the effective fiber diameter. The effective fiber diameter growth is inferred from filter pressure drop, which may in turn be a function of non-uniform tackifier application including blocked filter pores.

CHAPTER 6

DISCUSSION

A number of researchers (Davies, 1973; Davis *et al.*, 1994; Hinds, 1982) have reported on the phenomenon of particle bounce observed at velocities in excess of 1 m/s, where inertial impaction should play a dominant role. Ellenbecker, *et al.* (1980) appears to be the first to correlate particle adhesion with kinetic energy. In that study, particle adhesion probability, h, was defined as the ratio of the experimental single fiber collection efficiency, η'_I, and the theoretical single fiber efficiency, η_I:

$$h = \frac{\eta'_I}{\eta_I} \tag{16}$$

A value of h = 1.0 suggests that there is complete adhesion upon particle-fiber impact; whereas a value of zero would imply that the adhesion probability was zero, or that all particles bounced off of the fiber. The single fiber efficiencies are used since they are independent of filter configuration and depend only on the inertial impaction parameter, ψ, as previously defined.

The experimental single fiber efficiency may be back calculated knowing that the overall efficiency of a filter is exponentially related to the filter solidarity, S, and the sum of the single fiber efficiencies due to diffusion, interception, and inertial impaction. In this study, the components of diffusion and interception are not considered since they are negligible at these high air velocities. Rearranging terms in Equation (6) yields

$$\eta'_I = \frac{-\ln(1 - \eta_0)}{S} \tag{17}$$

where η'_I is the experimental single fiber efficiency due to inertial impaction, and η_0 is the experimental overall filter efficiency measured from the test stand.

Using the Ellenbecker, *et al.*, (1980) approach to particle bounce theory, modified by the Whitby (1965) theory for inertial impaction, the adhesion probability was calculated and plotted versus kinetic energy for velocities of 75-300 cm/s and a particle size of 3 µm. These conditions were chosen since, as Figure 5-1 shows, particle bounce is more prevalent at this condition than at other conditions which were studied. The lower curve of Figure 6-1 shows the results of the untreated controls. The control plot shows the near linear relationship between adhesion probability, h, and particle kinetic energy, clearly indicating that the adhesion probability decreased as kinetic energy was increased. Extrapolation of this curve to the origin where h = 1.0 suggests that bouncing may not occur for kinetic energies of less than approximately 10^{-15} J. For particles with an E_k greater than 10^{-15} joules, h progressively decreases, suggesting that particle bounce was largely responsible for increased penetration at the higher velocity/particle size conditions. This data agrees with that of previous studies (Ellenbecker, et al., 1980; Phillips, et al., 1995).

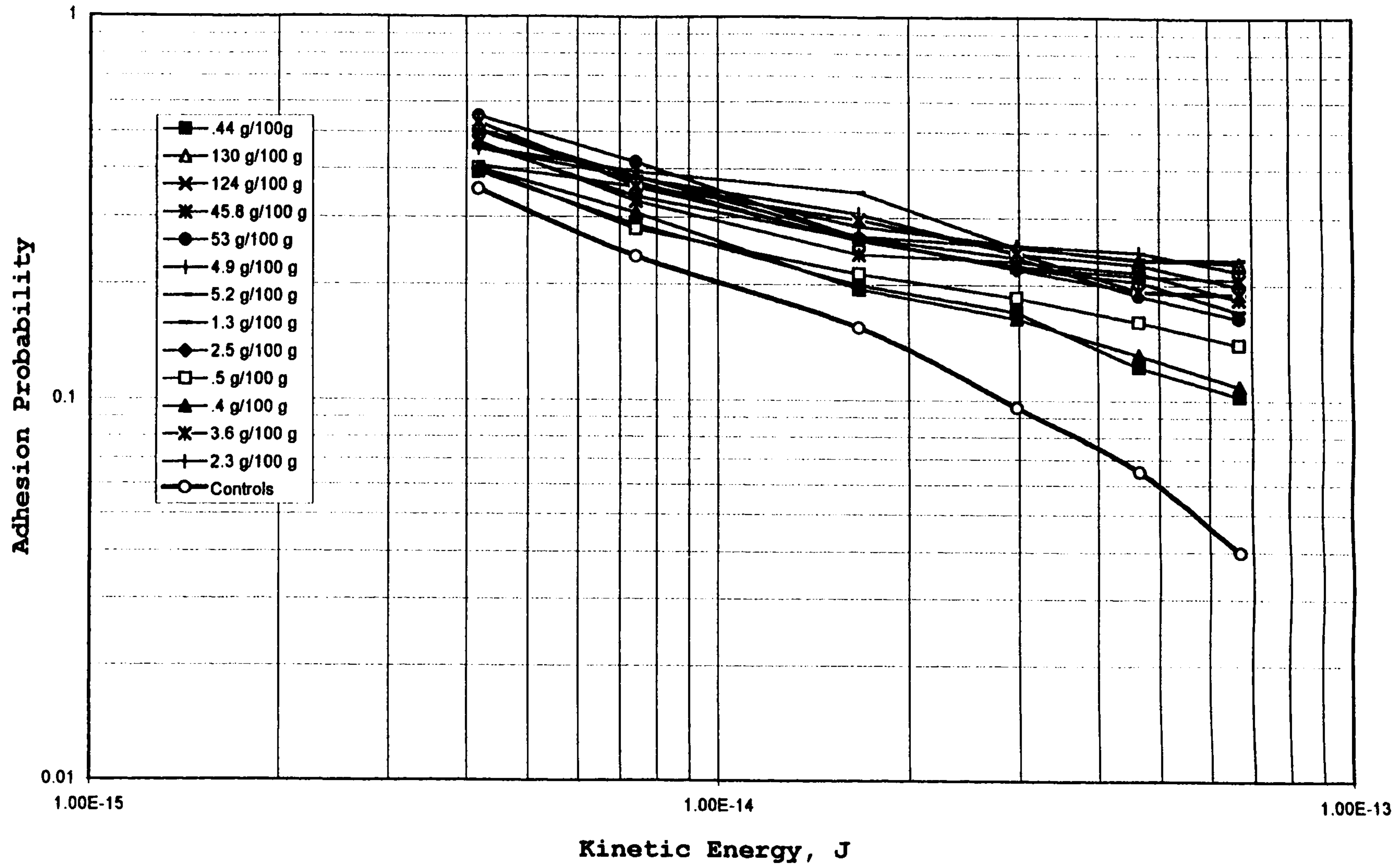

Figure 6-1. Adhesion Probability vs. Kinetic Energy (For Various Quantities of Tackifier Add-On)

In investigating the ability of the tackifier to inhibit particle bounce, the adhesion probability vs. kinetic energy curves were plotted for each of the filters which were treated with the tackifier, as shown in Figure 6-1. The scatter in the data of Figure 6-1 indicates the level of difficulty in controlling the exact quantity of tackifier applied, yet the data clearly show that the tackifier improves the particle adhesion probability at high kinetic energies(i.e., kinetic energies above 10^{-15}J). Thus, the laboratory results indicate a definite improvement in the particle adhesion probability across the range of values tested for all quantities of tackifier. However, no level of tackifier add-on was found to increase the adhesion probability back to a value of 1.0, eliminating particle bounce.

It may be simpler to evaluate the data in Figure 6-1 by a closer inspection of the extremes, e.g., the data points corresponding to 75 cm/s (Ek = 4.17E-15 J) and 300 cm/s (Ek = 6.68E-14 J). At conditions of Ek = 4.17E-15 J, the control values of adhesion probability ranged from h = 0.33 to h = 0.39. The range is given on the chart since values of zero add-on cannot be plotted on log scales. The minimum detectable add-on quantity was about 0.4 g add-on / 100 g filter. Figure 6-2 shows a significant increase in adhesion probability after the application of tackifier, but in no case does the adhesion probability approach a value of 1.0. Indeed the adhesion probability tends to peak at a value of 0.46 to 0.5, and it is reasonable to suggest that an application of 2-3 g tackifier / 100 g filter is sufficient to achieve this adhesion probability. For the conditions of Ek = 6.68E-14 J, the controls ranged from h = 0.032 to h = 0.048. At the minimum detectable concentration of

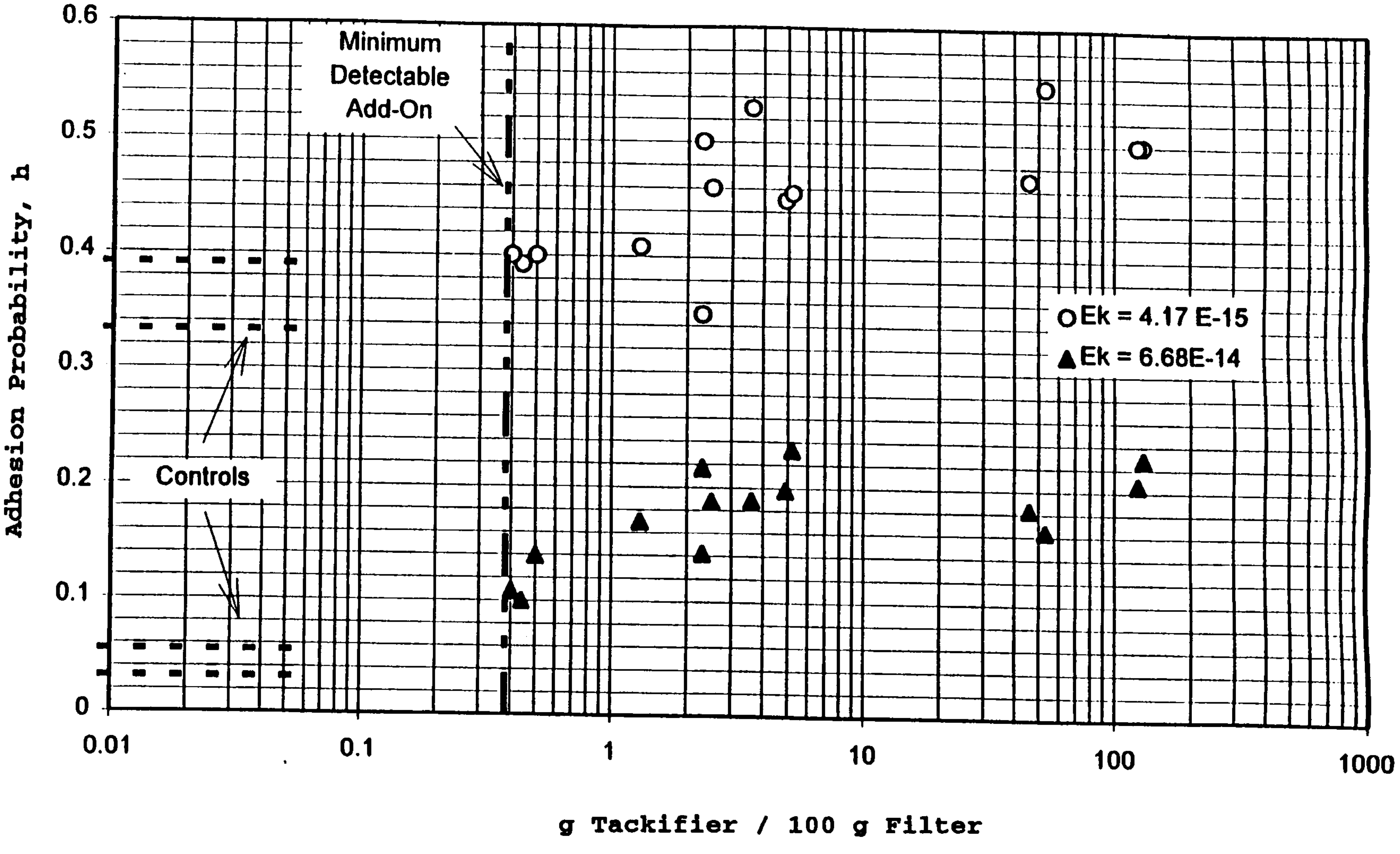

Figure 6-2. Particle Adhesion Probability vs. Tackifier Add-On

tackifier, the filters had already exhibited an improvement in adhesion probability. Upon the application of 2-3 g tackifier /100 g filter, the adhesion probability tended to peak at approximately 0.19 to 0.2, which is still substantially less than that predicted by theory.

CHAPTER 7

CONCLUSIONS

The ASTM Filtration Test Stand reported on herein provided a very reliable and versatile research platform with which to conduct indoor air quality research. Filtration efficiencies in this study were evaluated at velocities from 3 to 350 cm/s, using both wet and dry aerosols.

Adhesion probabilities were determined for monodispersed PSL particles, as well as cold polydispersed DOP, and correlated with particle kinetic energy. For dry particles it was observed that bounce was improbable at particle kinetic energies less that approximately 10^{-15} joules. This concurs reasonably with experimental data from other researchers using different materials.

The use of tackifiers can improve the efficiencies of indoor air quality filters operating at high velocities (1 - 2 m/s). This is due to the fact that these velocities impart high kinetic energies to the particles, and this kinetic energy is believed to cause these particles to bounce upon impact with the filter fibers. The tackifier increases the adhesion probability upon impact. However, filter efficiency is unimproved at low filtration velocities, or kinetic energies, when tackifier is applied. Hence, a tackifier may not be useful for improvement of filtration efficiency, in those cases where there is already a low facial velocity, such as a pleated media, and where diffusion and interception are the more dominant mechanisms.

Existing filtration theory tends to agree well with data derived from liquid aerosols, but the behavior of dry aerosols, such as PSL microspheres, departs significantly from the theory. By using the correlation's of adhesion probability investigated herein for particle kinetic energies in excess of 10^{-15} J, the collection of dry solid particles in fibrous media may be more accurately predicted.

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APPENDIX

A.1 RAW DATA FOR FIGURE 5-1 (CONTROL)

V cm/s	ΔP inches w.g.	0.6 μm Particle Size PSL η %	DOP η %	Theory η %	1.0 μm Particle Size PSL η %	DOP η %	Theory η %
3	.05	82.2	78.4	28.1	81.5	67	41.13
10	.33	79	60.5	20.9	76.6	63.5	37.26
20	.52	78.4	30.5	18.6	75.9	72	38.3
40	1.07	81.6	47.4	18.5	87.4	85	49.5
75	1.9	87	76.7	27.3	98.1	94	79.7
100	2.9	91.2	85.5	39.2	99.1	98.5	91.63
125	3.5	93	89	52.7	99.6	99.5	96.75
150	4.2	95.5	91.5	65.3	99.7	99.85	98.73
175	4.9	96.2	95	75.6	99.8	99.91	99.48
200	5.8	96.6	95.8	83.3	99.7	99.91	99.776
225	6.4	96.4	96.6	88.9	99.65	99.95	99.896
250	7.5	96.6	97.2	92.6	99.67	99.986	99.95
275	8.2	96.4	97.6	95.2	99.4	99.99	99.973
300	9.1	95.8	97.8	96.8	99.3	99.991	99.985
325	9.8	95.1	97.8	97.9	98.6	99.993	99.991
350	10.8	93.3	97.9	98.6	98.2	99.986	99.994

v cm/s	ΔP inches w.g.	2.0 μm Particle Size PSL η %	DOP η %	Theory η %	3.0 μm Particle Size PSL η %	DOP η %	Theory η %
3	.05	98	95	76.47	99.6	99.4	94.57
10	.33	99.3	97	79.48	99.93	99.82	97.84
20	.52	99.92	99.6	89.35	99.995	99.94	99.72
40	1.07	99.97	99.7	98.41	99.98	99.95	99.992
75	1.9	99.98	99.93	99.95	99.8	99.996	99.998
100	2.9	99.9	99.997	99.992	98.5	x	99.99995
125	3.5	99.5	99.995	99.9979	98	x	99.99998
150	4.2	99.5	99.9988	99.9992	95	x	99.99998
175	4.9	99	99.999	99.9996	90	x	99.99998
200	5.8	98.5	x	99.9997	81	x	99.99999
225	6.4	98	x	99.9998	77	x	99.99999
250	7.5	96	x	99.99991	68	x	99.99999
275	8.2	91	x	99.99993	62	x	99.99999
300	9.1	90	x	99.99994	53	x	99.99999
325	9.8	85	x	99.99995	50	x	99.99999
350	10.8	90	x	99.99996	45	x	99.99999

A.2 HIGH E_K TACKIFIER DATA

3 μm PSL SPHERES

		Sample #54		Sample #55		Sample #56		Sample #57	
v cm/s	Ek, J	DP, in. w.g.	η, %	DP, in. w.g.	η, %	DP, in. w.g.	η, %	DP, in. w.g.	η, %
75	4.17E-15	2.5	99.6	2.9	99.6	2.8	99.6	2.3	99.6
100	7.42E-15	3.3	98.7	3.85	99.2	3.7	99.1	3.1	98.7
150	1.67E-14	4.7	96	5.4	98	5.1	97.8	4.3	97
200	2.97E-14	6.4	94	7.5	98	7.2	96.9	6.0	97
250	4.64E-14	8.45	87	9.7	97.6	9.3	96.6	7.8	96.5
300	6.68E-14	10.3	82	11.5	97.6	11.0	96.5	9.3	94.4
Add-On, g/100g		0.44		130		124		45.8	
D_{eff}, μm		6.6		14.97		14.16		10.2	

		Sample #58		Sample #59		Sample #60		Sample #61	
v cm/s	Ek, J	ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %
75	4.17E-15	2.25	99.8	2.2	99.7	2.4	99.8	2.45	99.7
100	7.42E-15	3.0	99.5	3.0	99.5	3.25	99.7	3.4	99.6
150	1.67E-14	4.2	97.7	4.2	99	4.5	99.6	4.7	98.7
200	2.97E-14	5.8	97	5.8	97.6	6.2	98.3	6.5	97.6
250	4.64E-14	7.5	94.2	7.6	97.1	8.2	97.9	8.5	96.9
300	6.68E-14	9.0	91.9	9.1	95.6	9.9	97.9	10.3	94.6
Add-On, g/100g		53.0		4.9		5.2		1.3	
D_{eff}, μm		10.5		7.25		7.14		6.83	

v cm/s	Ek, J	Sample #62		Sample #63		Sample #64		Sample #67	
		ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %
75	4.17E-15	2.25	99.8	2.0	99.4	2.8	99.8	2.1	99.9
100	7.42E-15	3.2	99.3	2.8	97.8	3.8	99.4	3.1	99.5
150	1.67E-14	4.5	98.4	3.9	95.5	5.3	96.8	4.3	99.0
200	2.97E-14	6.1	97.1	5.3	93.6	7.3	94.8	5.7	97.9
250	4.64E-14	8.0	95.6	7.0	91.0	9.5	91.0	7.5	95.5
300	6.68E-14	9.7	95.4	8.4	87.8	11.3	86.4	9.1	95.3
Add-On, g/100g		2.5		0.5		0.4		3.6	
D_{eff}, μm		7.2		6.27		6.62		6.17	

v cm/s	Ek, J	Sample #68		Sample #69	
		ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %
75	4.17E-15	2.45	99.9	1.7	97.9
100	7.42E-15	3.3	99.7	2.3	96.7
150	1.67E-14	4.6	99.0	3.3	95.0
200	2.97E-14	7.4	98.5	4.4	91.2
250	4.64E-14	8.3	98.3	5.7	88.8
300	6.68E-14	9.9	97.4	7.0	84.7
Add-On, g/100g		2.3		2.3	
D_{eff}, μm		6.46		6.53	

A.3 HIGH E_K CONTROL DATA

3 µm PSL SPHERES

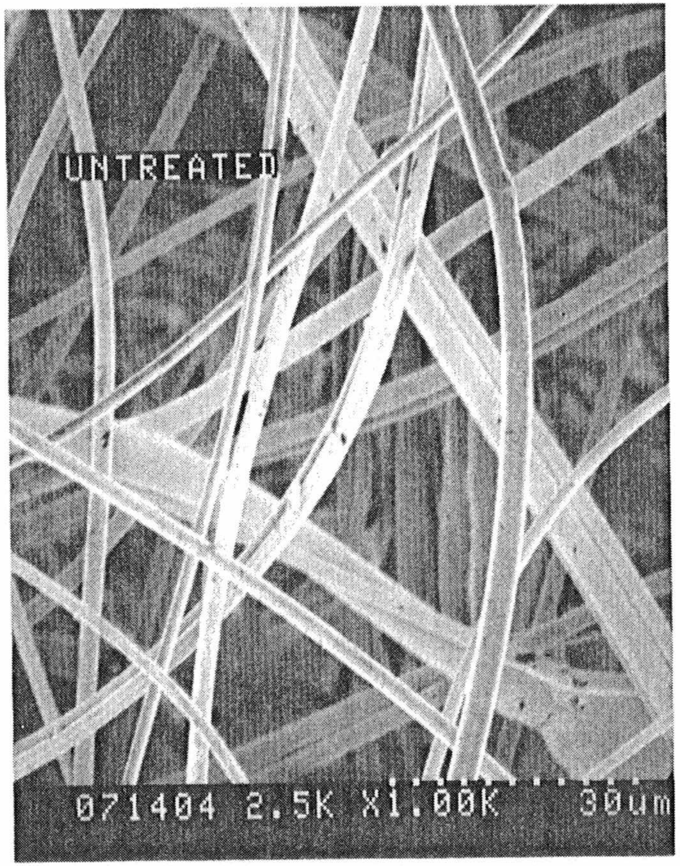
		Sample #21-A		Sample #21-B		Sample #21-C		Sample #21-D	
v cm/s	Ek, J	ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %	ΔP, in. w.g.	η, %
75	4.17E-15	2.1	98.8	2.2	99.3	2.25	98.9	2.4	99.1
100	7.42E-15	2.9	97.2	3.0	97.1	3.2	95.2	3.3	96.5
150	1.67E-14	4.0	91.7	4.2	93.2	4.5	87.2	5.5	89.3
200	2.97E-14	5.7	79.4	5.8	78.6	6.2	73.0	6.2	79.9
250	4.64E-14	7.5	70.3	7.7	66.1	8.15	60.0	8.2	60.7
300	6.68E-14	9.1	51.9	9.3	46.9	9.9	47.6	10.0	41.8
Add-On, g/100g		0		0		0		0	
D_{eff}, µm		7.45		7.33		7.09		6.98	

A.4 LOW E_K TACKIFIER DATA

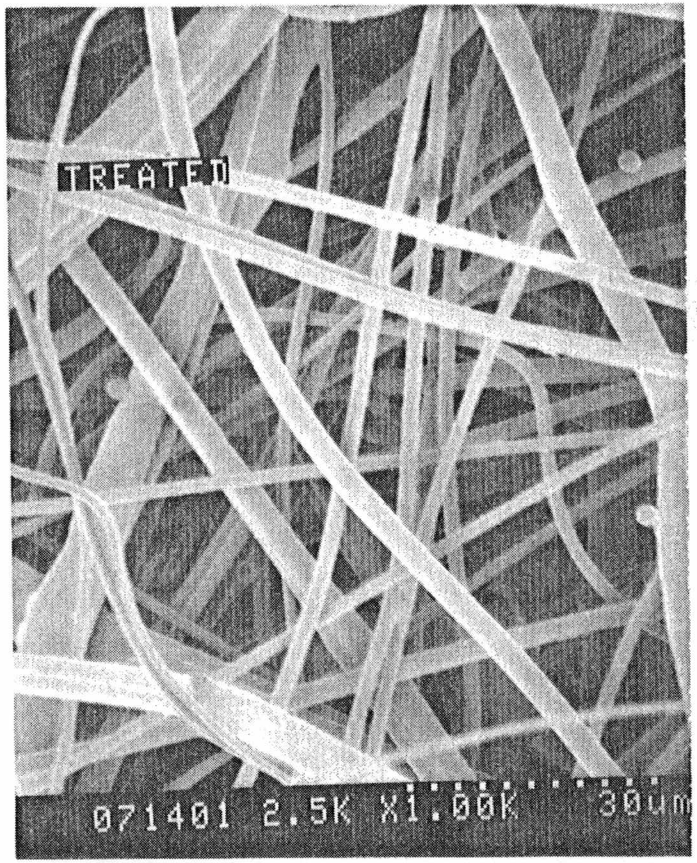
1 µm DOP @ 40 cm/sec

Sample #	Add-On, g / 100 g	ΔP, in. w.g.	η,%
55	130	1.23	88.5
58	53	1.01	85
61	1.3	1.19	85.4
63	.5	1.0	85.7
64	.4	1.24	92.2
67	3.6	1.0	89
68	2.3	1.11	91.2
69	2.3	.8	76.7
21-C (control)	0	1.07	88.6

A.5 PHOTOMICROGRAPHS OF FILTER MEDIA



Untreated medium shows heterogeneity of polypropylene melt-blown fibers.



Treated medium does not reveal tackifier coating. Also note PSL Spheres which had been collected on the medium. The PSL Spheres appear to be about 3 µm in diameter.

VITA

Bruce Alan Phillips was born in Shreveport, Louisiana on October 27, 1962. He attended schools in the Shreveport-Bossier City area, and subsequently attended Louisiana Tech University in Ruston Louisiana. He received a Bachelor of Science in Petroleum Engineering in 1984.

Alan was commissioned as an Officer in the United States Marine Corps upon completion of his university studies. He completed Naval Flight School, including aircraft carrier landing qualifications, and was designated a Naval Aviator. His duties in the Marine Corps included the piloting of single-engine jet aircraft, as well as the staff duties of a Squadron Logistics & Supply Officer.

After military service, Alan flew as a commuter airline pilot for Continental Express Airlines, based in Bangor, Maine, and Newark, New Jersey. He has an Airline Transport Pilot rating and has piloted many commercial, military, and light civil aircraft.

An interest in an environmental career came after a volunteer internship with Chantiers Concordia in the Picardie region in France. This was an international experience with river restoration, and also provided Alan with an opportunity to improve his French language skills.

After Europe, Alan and an old college friend started an environmental consulting business called Waste Reduction Technologies in June, 1992. The enterprise was established to assist Tennessee manufacturers with state and federal requirements concerning the management of process waste water discharges, air emissions, as well as solid and hazardous wastes. The firm was incorporated the following year and is still a profitable business as of this writing.

Alan received his Master of Science in Environmental Engineering in December, 1995. He is currently married, and employed as an Environmental Engineer with CH2M Hill in San Antonio, Texas.