A Modified Elutriation Device to Measure Particle Settling Velocity in Urban Stormwater Runoff

A THESIS SUBMITTED TO THE FACULTY
OF THE GRADUATE SCHOOL OF THE UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULLFILLMENT OF THE REQUIRMENTS FOR THE DEGREE OF MASTER OF SCIENCE

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August 2010

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1. Introduction

As point sources of pollution are more widely regulated, the impacts associated with non-point sources of pollution have become more apparent. Specifically in urban areas, untreated stormwater runoff has the potential to degrade the quality of receiving water bodies. To investigate the potential impacts from urban runoff, the United States Environmental Protection Agency, USEPA, commissioned a study that found high levels of contamination associated with runoff from street surfaces (USEPA 1972). Subsequently, the USEPA established the Nationwide Urban Runoff Program, NURP, which was implemented to collect information about stormwater and provide municipalities, regulators, and consultants with a rational basis for design and implementation of stormwater controls. Results from the NURP studies indicated high levels of contaminants, especially heavy metals and nutrients, in urban runoff.

Municipalities and other agencies have since implemented management practices to improve runoff quality before it is discharged into the environment. The primary objective of many management practices is to remove particles from urban runoff because particles serve as a carrier for heavy metals and can degrade water quality by increasing turbidity. When designing treatment devices to remove particles from urban runoff, practitioners generally use a mean settling velocity distribution determined from the NURP studies. Subsequent studies, however, indicate the NURP distribution may not accurately represent typical runoff particle size distributions for many watersheds.

Designing devices to improve water quality through sedimentation of particles involves a variety of considerations. For example, the main property related to removal efficiency of devices is particle settling velocity. Particle settling velocity can be calculated using empirical equations and assumptions about particle size and particle density. Making assumptions about unknown particle characteristics can be problematic, and it is more accurate to directly measure the settling velocity of particles in urban stormwater runoff. A number of methods have been developed to directly measure setting velocity distribution. One of these methods, elutriation, has been investigated as a potential supplement or replacement for other techniques.

Elutriation is a method to directly measure settling velocity distributions of particles. In water elutriation devices water flows upward through a column and a suspension of particles is introduced. Particles with settling velocities less than the upward fluid velocity in the column will eventually be flushed out of the column, and particles with settling velocities greater than the upward fluid velocity will be retained in the column. If a series of columns with varying diameters thus varying upward velocities is used, a settling velocity distribution of the particles can be calculated based on the upward velocity of water in the columns and the mass of particles retained in each column.

Elutriation devices have been applied to measure the settling velocity distributions of sediments in a river (Walling & Woodward 1993) and particles in combined sewer overflows (Krishnappan *et al.* 2004, Marsalek *et al.* 2006). The devices have been effective for these applications, and they can be expanded to measure the settling velocity distribution of particles in urban stormwater runoff. Modifications to the devices used in previous experiments have been made so the device is easier to use, cheaper and easier to manufacture, and more appropriate for implementation in the field. The impact of particles in stormwater and the modified elutriation device are the topics of this thesis.

2. Background: Particles in Stormwater

Previous researchers have investigated the importance of particles in stormwater. Particles in stormwater have been characterized by calculating settling velocity from particle size, measuring settling velocity distribution of particles in runoff, measuring particle size distribution for particles on street surfaces and in runoff, measuring density of stormwater particles, and determining pollutants associated with particles. Additionally, the importance of particle size and settling velocity distribution in stormwater impacts the performance of stormwater management practices.

2.1. Settling Velocity Calculations

Since many devices rely on sedimentation to remove particles from stormwater, particle size distributions must be converted to settling velocity distributions for design purposes. Equations to convert particle size into settling velocity have been developed using traditional particle physics and experimental studies. The following section describes the details of the equations.

Settling velocity, w_s, can be determined using a balance of gravity and drag forces at the terminal settling velocity. The terminal settling velocity assumption is typically valid for particles falling in liquids. For very small particles the low inertia results in a derivation of Stokes' law from the equations of motion, which relate settling velocity to particle size, particle density, and fluid viscosity (Vanoni 1975). The version of Stokes' law shown in Equation 2.1 assumes spherical particles.

$$w_s = \frac{(\rho_s - \rho) g D^2}{18\mu} \qquad \text{Equation 2.1}$$

where:

ρ_s = density of the particle
ρ = density of the fluid
g = gravitational constant
D = diameter of smooth sphere
μ = dynamic viscosity

As diameter increases, the increased inertia of the particles results in fluid separation, and Stokes' flow is no longer accurate. When particle size becomes sufficiently large, the separation wake behind the particle becomes fully turbulent. The drag coefficient acting on the particle is close to a constant, resulting in a settling velocity characterized by Equation 2.2 (Mays 2005).

$$w_s = \left[\frac{4}{3}\frac{D}{C_D}\left(\frac{\rho_s}{\rho} - 1\right)g\right]^{1/2} \qquad \text{Equation 2.2}$$

where:

C_D = drag coefficient (0.44 for smooth sphere)

Particles in urban runoff, however, are not perfectly spherical (Roberts *et al.* 1988b) so a different approach must be used to determine settling velocity. Dietrich (1982) investigated the effects of particle shape, particle roundness, and particle texture on settling velocity. Shape is quantified using a microscope to measure the short, long, and intermediate axes of a particle. Particle roundness is determined by a Powers roundness factor. Powers roundness factor is a subjective measurement assigned to particles after evaluating their "roundness" under a microscope. Dietrich combined the factors describing particle properties with particle physics to generate complex equations describing the settling velocity of non-spherical particles.

Researchers since Dietrich have developed simplified settling velocity equations for natural sediment particles (Bhargava & Pajagopal 1992, Cheng 1997, Swamee & Ojha 1992, Zhu & Cheng 1995). A summary of settling velocity equations is provided in Sansalone *et al.* (2009). What are desired in predictive equations for settling velocity are the ability to predict outside of the range of data used to develop the equation, simplicity, and the ability to change coefficients based upon observed characteristics of the sediment particles. Ferguson and Church (2004) simplified the Dietrich equations by determining a single equation that estimates particle settling velocity for a range of conditions, given in Equation 2.3. The

Ferguson and Church equation approaches Stokes' law for very small spherical particles and a constant drag coefficient for large particles. The equation is fit to experimental observations in the transitional settling velocity range. Particle shape and texture are addressed by using two different coefficients (C_1 and C_2) that are adjusted for various conditions as shown in Table 2.1. In the table "sieve diameters" represents particles whose size have been characterized using sieves, and "nominal diameters" refers to the equivalent spherical diameter of a particle based on its volume. The values for perfectly angular grains are used for grains that are highly irregular and represent approximate maximum values for C_1 and C_2.

$$w = \frac{RgD^2}{C_1 \upsilon + (0.75 C_2 RgD^3)^{0.5}} \qquad \text{Equation 2.3}$$

where:

$R = (\rho_s - \rho)/\rho$

C_1, C_2 = Coefficients with suggested values of Table 2.1

Table 2.1. Values for C_1 and C_2 for Ferguson and Church (2004) equation

Particle Description	**C_1**	**C_2**
Smooth sphere	18	0.4
Perfectly angular grains	24	1.2
Intermediate grains (nominal diameters)	20	1.1
Intermediate grains (sieve diameters)	18	1.0

Despite its simplicity, Ferguson and Church's equation is a good substitute for Dietrich's equations in practical applications. Particle settling velocity depends on particle size, density, shape, roundness, and surface texture. Most practical applications involve a collection of heterogeneous and diverse particles, and characterization of the parameters for every particle in an application of Dietrich's equation to the distribution is not reasonable. Ferguson and Church's equation overcomes this problem because it does not utilize a direct measurement of particle shape and roughness like Dietrich's equations. Instead, the particle characteristics are collapsed into two constants based on both theory and empirical research. The equation and its corresponding coefficients fit well with previously collected particle settling data so it is a reasonable equation for calculating settling velocity (Ferguson & Church 2004).

2.2. Methods for Measuring Particle Size and Settling Velocity Distributions

Particles in urban runoff have been characterized by both settling velocity distribution and particle size distribution. The most common methods to measure settling velocity include the Aston column, the Brombach column, the USEPA settling column, and elutriation devices (Aiguier *et al.* 1996, Krishnappan *et al.* 2004). Particle size distribution is measured using separation, light refraction, or electrical resistance (Grant *et al.* 2003). The various techniques are reviewed in the following sections.

2.2.1. Passive Settling Devices

Passive settling devices directly characterize particle settling velocities in a quiescent water column. Other methods measure settling velocity in flowing water or only measure particle size and rely on equations to calculate settling velocity based on size and other particle properties. Lucas-Aiguier *et al.* (1998) described four methods for measuring the settling velocity distribution of particles in stormwater. The methods include the Umwelt- und Fluid- Technik (UFT), the CERGRENE protocol, the Aston column, and the Camp protocol. Samples used in the Aston and UFT methods are initially settled to remove larger particles, and the samples used in the CERGRENE method are wet sieved. Samples used in the Camp protocol do not utilize any type of pretreatment. Settling depths for the methods range from 0.2 m to 1.8 m, and the settling velocities measured range from 0.0014 to 8 cm/s depending on the method used. The details of the four methods are described in the Lucas-Aiguier *et al.* (1998) article. An Imhoff cone is also used in studies to separate particles in two categories. “Settleable” particles are characterized as particles that settle in the Imhoff Cone after one hour, and particles that remain suspended after one hour are not “settleable.” (Sansalone & Kim 2008). Studies utilizing settling devices to characterize the settling velocity distribution of particles on urban surfaces or in urban runoff are listed in Table 2.2.

Table 2.2. Studies utilizing settling methods to characterize particles

Study	**Methods used**
Whipple & Hunter 1981	Glass settling column
Lucas-Aiguier *et al.* 1998	UFT, CERGRENE, Camp, Aston
Aiguier *et al.* 1996	Aston, UFT, CERGRENE
Greb & Bannerman 1997	Pipette (<62μm), Accumulation (>62 μm)
Andral *et al.* 1999	Andreasen pipette, sedimentation column
Sansalone & Kim 2008	Imhoff cone
Sansalone *et al.* 2009	Imhoff cone, 152mm settling column

Measurement of settling velocity distribution has distinct advantages over size distribution methods. Since particle settling velocity depends on shape, texture, and density, direct measurement of settling velocity provides a more accurate representation of the actual settling velocity distribution. Settling velocity measurements can also be conducted with relative simple and inexpensive methods.

Despite the advantages, devices used to directly measure settling velocity suffer from challenges. Some methods require up to 32 hours to operate (Whipple & Hunter 1981). Particles in stormwater have been found to aggregate after 6 hours (Li *et al.* 2005, so the long analysis time may affect the settling velocity distribution measured. In addition, settling columns operate under quiescent conditions, which is not the case in most stormwater unit operations (Krishnappan *et al.* 2004). Measured settling velocity distributions have also been shown to vary among the different experimental procedures for identical samples (Lucas-Aiguier *et al.* 1998). Finally, analysis of pollutants associated with particles of different settling velocities cannot be determined because the sub-samples collected from the methods do not contain enough particles.

2.2.2. *Elutriation to Measure Particle Settling Velocity Distribution*

Elutriation is a separation method where finer, lighter particles are separated from coarser, heavier particles by means of an upward stream of fluid. In water elutriation devices a suspension of particles is pumped upward through a series of columns with increasing diameters. Particles with settling velocities less than the upward velocity in a column are flushed out of the column, and particles with settling velocities greater than the upward velocity are retained in the column. The upward velocity of the fluid stream in a column can be determined from the flow rate and column diameter. When the device is operated, the particles retained in each column have a distinct range of settling velocities. Column water velocities and particle mass retained in each column can be used to develop the settling velocity distribution of the particles.

Elutriation devices have been applied to measure the settling velocity distribution of sediments in a river (Walling & Woodward 1993) and particles in combined sewer overflows (Krishnappan *et al.* 2004, Marsalek *et al.* 2006). Like settling columns, elutriation devices directly measure particle settling velocity. They provide an advantage over settling columns because they operate under dynamic, non-quiescent conditions rather than quiescent conditions that exist in settling columns. The dynamic nature is important because studies have shown turbulence can have an impact on particle drag coefficients, which ultimately has an effect on settling velocity (Doroodchi *et al.* 2008). Since the device only requires the operator to turn on a mixer and a pump, the operation of the device is simple and passive. Finally, the device separates particles into distinct settling velocity ranges, and the particles in each settling range can be analyzed for metals and other pollutants.

Elutriation devices do have limitations in their application for stormwater. Between 20 and 60 liters of stormwater sample is required for each test. Although operation of the device is simple, analysis of the results can be time and labor intensive because total suspended solids (TSS) or suspended solids concentration (SSC) tests must be conducted on each column in the elutriation device. In addition, time and flow constraints prevent the device from accurately measuring particles outside an approximate equivalent diameter range of 8 micrometers to 200 micrometers. Finally, research has shown that settling velocity distributions from elutriation devices more closely resemble distributions that would be expected from a laminar, parabolic flow profile in the column rather than the known turbulent and uniform flow profile (Hettler & Gulliver 2010). The particles in the individual columns are a mixture of sizes that would not be expected if uniform flow in the columns is assumed. To overcome this discrepancy a correction factor is used to obtain an accurate representation of the settling velocity distribution and, if desired, the pollutant concentration on various particle sizes. More detail about elutriation devices are provide in the following chapters.

2.2.3. *Sieving*

Sieving is a separation method used to measure particle size distributions. Sieves with various opening sizes separate particles, and particles are weighed to compute the mass corresponding to each sieve. A smooth curve is fit through the segmented sizes, which results in a weight-based size distribution. Two methods are typically used when using sieves to characterize particle size distribution. The methods are known as dry sieving and wet sieving.

Before particles are dry sieved, they must be dried and prepared according to ASTM Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants (D421-85). The dried mass of particles is then passed through a stack of standard sieves with the openings of each sieve decreasing in size as the particles pass from the top of the stack to the bottom. Particles larger than the sieve opening are retained on the respective screen, while smaller particles pass through to the next sieve. Detailed methodology for dry sieving is found in ASTM Standard Test Method for Particle-Size Analysis of Soils (D422-62). While wet sieving uses the same general concepts as dry sieving, it incorporates the addition of distilled water to wash particles through the screens. The protocol for wet sieving is described in ASTM Standard Test Method for Materials Finer than 75-μm (No. 200) Sieve in Mineral Aggregates by Washing (C117-04).

In general, wet sieving is used rather than dry sieving when a sample has an abundance of particles less than 75 micrometers. The use of distilled water is important because the smaller particles can aggregate and clog the sieve openings. Some researchers avoid using wet sieving when chemical analysis of the particles is to be conducted, however, because the distilled water can remove some of the metals or other pollutants from the surface of particles. Studies using sieving to characterize the size distribution of particles on urban surfaces or in urban stormwater runoff are listed in Table 2.3.

Using sieving to characterize particle size distributions has advantages including the separation of particles into various size categories. Once separated, properties of particles within a specific size range can be determined. Studies have used the separation to characterize pollutants associated with various size ranges (Bathi *et al.* 2009, Sansalone *et al.* 1999, Viklander 1998) and specific surface area of particles within a size range (Sansalone *et al.* 1997). Sieving is also a simple method that does not require complicated, expensive equipment or a significant amount of time.

Using only sieving to characterize the sizes of particles in stormwater, however, does have limitations. Particles are separated into distinct size ranges and weighed, so a large number of screen sizes must be used to obtain high resolution particle size distributions. This is countered by the measurable mass of particles that must be obtained to accurately measure the weight retained on each sieve. For applications measuring particles collected directly from street surfaces or treatment devices, collecting enough mass is typically not as difficult. If particles in runoff are to be characterized using sieving, however, tens of liters of runoff must be collected to ensure that a measurable amount of mass can be retained on each screen. Particles also tend to adhere together, especially at the lower sizes. This adhesion is the reason for the wet sieving technology, because the polarity of water will tend to pull these adhered particles apart. Finally, sieving provides information about a characteristic diameter of a particle. Since stormwater particles are not spherical, the orientation of the particle when it hits the sieve may determine whether or not it will be retained on the screen.

Table 2.3. Studies utilizing sieving methods to characterize particles

Authors	**Wet or Dry**	**Sieve diameters (μm)**
Grottker 1990	Wet	1600, 1000, 500, 250, 160, 80, 25
Xanthopoulos & Hahn 1990	Unspecified	1000, 200, 80
Sansalone *et al.* 1997, Sansalone *et al.* 1998	Dry	9500, 4750, 2000, 850, 425, 250, 150, 106, 75, 63, 53, 45, 38, 25
Viklander 1998	Both	8000-75
Andral *et al.* 1999	Wet	1000, 500, 100, 50
Sansalone & Tribouillard 1999	Dry	4750, 2000, 1400, 853, 599, 422, 251, 178, 152, 104, 75, 53, 44, 37, 25
Liebens 2001	Dry	2000 - 63
Cristina *et al.* 2002	Dry	4500 to 25
Furumai *et al.* 2002	Dry	250, 106, 45, 20
Vaze & Chiew 2004	Both	300, 150, 53
Lau & Stenstrom 2005	Dry	841, 250, 125, 100, 43
Murakami *et al.* 2005	Wet	2000, 250, 106, 63
Bathi *et al.* 2009	Dry	2800, 1400, 710, 355, 180, 90, 45
Lin *et al.* 2009	Dry	9500 to 25

2.2.4. *Particle Counting Devices Utilizing Lasers*

Devices utilizing light obstruction, diffraction, and scattering to measure size characteristics of particles are also used to measure particle size distribution. The devices use a highly focused beam of light and a corresponding light measurement technique to determine the number of particles of a specific size. Information about instruments operating with different light measurement techniques (obscuration, diffraction, dynamic) is provided in Li *et al.* (2005). The article also discusses the respective advantages and disadvantages of the specific devices. For example, light obscuration techniques measure sizes and do not depend on particle properties such as refractive index, but the technique may disrupt fragile flocs. Light diffraction techniques do not require complicated equipment calibration, but the concentration of particles can have an impact on results. Finally, dynamic light scattering techniques can characterize very small particles (down to 1 nm), but stabilizing the equipment takes a long time. Studies that utilized laser techniques to measure particle size distribution of stormwater solids are listed in Table 2.4.

Table 2.4. Studies utilizing laser devices to characterize particles

Authors	**Device and size ranges used**
Sansalone *et al.* 1998	HIAC/ROYCO 9064 (2 - 300 μm)
Andral *et al.* 1999	Coulter LS 130 (0.1 to 900 μm)
Jacopin *et al.* 1999	MALVERN (<2000 mm, <900 μm)
Legret & Pagotto 1999	Laser for <500 μm *
Drapper *et al.* 2000	Mastersizer S (<710 μm)*
Cristina & Sansalone 2003	HIAC-ROYCO (2 - 400 μm range)
Li *et al.* 2005	Nicomp AccuSizer 780 (2-1000 μm)
Kayhanian *et al.* 2008	LISST-portable (1.2 - 250 μm)

* *Sample pre-screened to remove particles larger than specified size*

Lasers provide many advantages over settling devices, elutriation devices, and sieving techniques. Devices utilizing lasers only require samples of a few milliliters to determine the particle size distribution. The devices also require a few minutes to operate so many samples can be analyzed in a short amount of time. In general, the interfaces of these devices are straightforward and easy to use. The laser devices also provide a high level of precision and generally provide more repeatable results. Since the precision allows particles in very small size ranges to be counted, the laser devices allow for a more robust analysis of particle size distribution. Finally, the devices can create distributions based not only on mass but also on the total number of particles.

Laser particle size analyzers do present issues when determining particle size distributions. Since the sample size required is so small, a very effective mixing technique is required to get a representative sub-sample. Additionally, many of the devices measure a characteristic length or cross-sectional area. Since stormwater particles are irregularly shaped, the parameter measured may not be representative of the actual particle. The maximum size of particles that can be measured with the devices is limited to between 200 and 1000 μm so other methods such as sieving must be employed to characterize the size distribution of particles larger than the upper limit. Li *et al.* (2005) indicates other limitations include the disruption of fragile flocs and the impact of solution concentration on the results. Again, as with all devices that measure particle size distributions, information about particle density, shape, and texture must be measured or assumed to estimate settling velocity distributions.

2.2.5. Particle Counting Devices Utilizing Electric Resistivity

Devices employing electric resistivity are also available to characterize particle size distribution. In the process an electrolytic solution is added to a sample containing particles. The device pulls particles through an orifice and measures the change in electric resistance between the two sides of the orifice. The device converts this change in electric resistance to a volume of the particle passing through the orifice, and the volume is converted to an equivalent spherical diameter. Studies utilizing electric resistivity to measure the size of particles related to stormwater runoff are listed in Table 2.5.

The advantages of devices using electric resistivity are similar to those related to laser particle size analyzers. The devices require less than 10 milliliters of sample to measure a particle size distribution, and analysis of a single sample only takes minutes. As a result, many samples can be analyzed very quickly from a single, larger sample. Devices utilizing electric resistivity also require minimal effort from the user and produce precise results. A distinct advantage of these devices is their ability to measure the volume of particles and convert it to an equivalent spherical diameter. While this method does not provide any information on particle density, shape, or texture, it is more accurate than measuring just a single length or cross-sectional area

Table 2.5. Studies utilizing electric resistivity to characterize particles

Authors	**Device and size ranges used**
Characklis & Wiesner 1997	Coulter ESZ (0.45 - 15 μm)
Roberts *et al.* 1988a	Coulter Counter (8.2 - 28 μm)
Westerlund & Viklander 2006	Coulter Multisizer II (4 - 120 μm)

Devices using electric resistivity to characterize particle size distribution have drawbacks. Since only a small amount of sample can be run through the device, an effective method to mix and separate a larger sample into representative sub-samples is necessary. Also, the range of particles measured by a single tube is limited by the size of orifice. In order to obtain a particle size distribution over a large range, aperture tubes on the device must constantly be switched, which becomes time-consuming for the operator. Even with different sized aperture tubes, the devices can only measure particles that become suspended and pulled through the orifice tube. The most notable disadvantage of electric resistivity is the electrolyte solution that must be added to the sample. The solution disrupts the chemistry of the original sample. The change in chemistry can disrupt flocs and have an impact on the true particle size distribution of the original sample.

2.3. Density of Stormwater Particles

Particle density is an important variable when calculating settling velocity from a particle size distribution. Generally, researchers and practitioners assume every particle in a distribution has a specific gravity similar to sand (2.50-2.65). Stormwater runoff, however, is composed of a variety of particles including organics, particles from tire wear, asphalt wear, pavement erosion, and metals from vehicle wear. The specific gravity of each of these particle types can vary significantly. For example, organic particles have a specific gravity close to 1, tire particles have a specific gravity around 1.25 (Murakami *et al.* 2005), natural quartz particles have a specific gravity around 2.65, and metals from vehicle wear can have specific gravities between 5 and 6 (Davis & McCuen 2005). It is possible to isolate the organic particles using APHA Standard Method for Fixed and Volatile Solids Ignited at 550^{o}C (APHA 2540E), but isolation of the metal particles has not been reported.

Researchers have used various techniques to characterize the density of stormwater particles. Density refers to the average density of all particles in a sample, which equals the total mass of solids divided by the total volume of the solids. The various methods include standards from the New Zealand Soil Bureau (1972); ASTM Standard Test Method for Specific Gravity of Soil Solids by Gas Pycnometer (D5550-06); AFNOR Standard Determination of Density of Solids in Powders and Liquids, Pycnometric Method (NF T20-053); and separation into categories by fluid (Murakami *et al.* 2005). In the method to separate particles into categories by fluid, particles are placed in a liquid of a known specific gravity (typically 1.6-1.7). Particles with a specific gravity lower than the fluid will float while others sink. A summary of studies measuring the density of stormwater particles and the methods used is provided in Table 2.6.

The specific gravity of particles in the studies ranges from 1.6 to 3.01 with the majority of measurements between 2.3 and 2.5. The latter range is less than what is generally assumed for stormwater particles. Incorrect assumptions about density have an impact on the design and performance of sedimentation practices because particle settling velocity decreases as particle specific gravity decreases. Assuming a specific gravity that is greater than the actual specific gravity of particles can result in undersized or underperforming stormwater sedimentation practices.

Table 2.6. Density measurements of particles in stormwater

Study	**Particle Collection**	**Methods used**	**Specific Gravity**
Andral *et al.* 1999	Runoff	ACCUPYC 1330 (helium pycnometer)	2.38-2.86
Jacopin *et al.* 1999	Stormwater trap sediments	NF T20-053	2.24
Sansalone & Tribouillard 1999	LPSF	ASTM D5550-93 (helium pycnometer)	2.70-3.01
Cristina *et al.* 2002	Snowmelt	ASTM D5550-93 (helium pycnometer)	2.86 (coarse), 2.75 (fine)
Zanders 2005	Road surface particles	New Zealand Soil Bureau (1972)	2.14 - 2.53
Murakami *et al.* 2005	Road dust	Separation by fluid with SG 1.7	Light particles 4% by mass
Anta *et al.* 2006	Runoff	Average from other research	2.04
Lin *et al.* 2008	LPSF at 4 locations	ASTM D5550-93 (helium pycnometer)	2.14-2.40
Kayhanian *et al.* 2008	Runoff and sediment	ASTM D5550-06	1.6-1.8
Sansalone *et al.* 2009	LPSF	ASTM D5550-94 (helium pycnometer)	2.15-2.61

Specific gravities for discrete size ranges can be measured if particles have been separated using sieves (Li *et al.* 2006). Density measurements, even when calculated for a sub-set of discrete size ranges, still lack sufficient detail to accurately estimate pollutant removal by settling. Some pollutants tend to be associated with particles having specific gravities different from the specific gravity and would not settle at the same rate as a silica particle of the same size. For example, poly-cyclic aromatic hydrocarbons, PAHs, tend to associate with organic particles, which have a specific gravity less than the specific gravity (Bathi *et al.* 2009). If total removal of PAHs associated with particles is calculated using the specific gravity, removal will be overestimated because particles containing PAHs have lower settling velocities than the average particles.

2.4. Particle Size Distributions from Literature

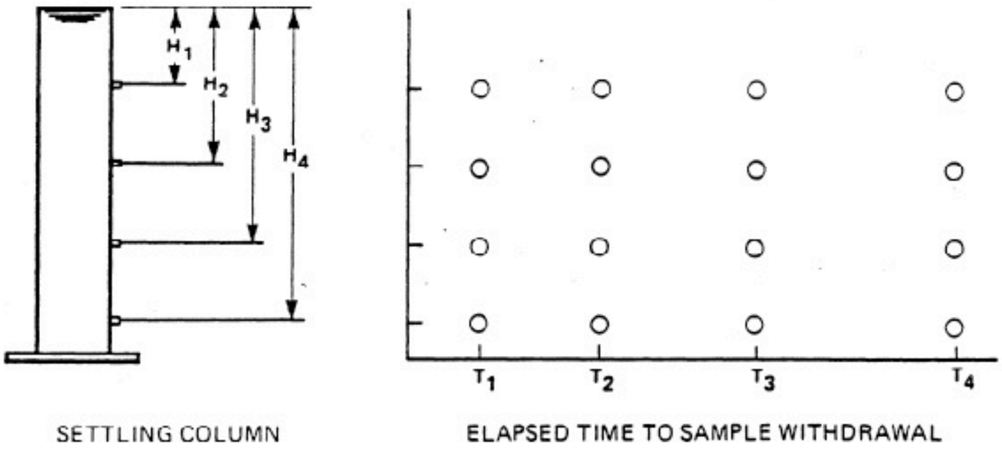
Many studies have investigated the particle size or settling velocity of particles in urban stormwater runoff. One of the first formal investigations of settling velocity distribution was from the NURP studies conducted by the USEPA (1983). While this distribution is the most commonly used in design, subsequent researchers have developed particle size and settling velocity distributions for particles from many other stormwater runoff sources. From the subsequent studies researchers found the settling velocities estimated from particle size distributions vary substantially from the NURP distribution. Studies have been conducted at sites located throughout the United States and other parts of the world, and sampling and measurement techniques vary widely among studies. The following sections introduce the various studies that have investigated particle size distribution or settling velocity distribution of particles associated with urban runoff.

2.4.1. Nationwide Urban Runoff Program

The NURP studies were implemented to collect information about stormwater and provide municipalities, regulators, and consultants with a rational basis for design and implementation of stormwater controls. A settling velocity distribution from NURP was reported in a paper detailing methods for sizing detention basins (USEPA 1986). The NURP distribution is regularly utilized in the design of stormwater Best Management Practices (BMPs) and water quality models (e.g., P8 Urban Catchment Model).

The original NURP distribution is not included in the final report of the NURP studies, but it appears in a USEPA paper about the analysis of dry detention basins (USEPA 1986). The report explains the methodology used to generate the commonly used distribution. First, automatic samplers were used to collect runoff samples at thirteen different sites throughout the United States. The settling velocity of runoff particles was then determined using the USEPA settling column procedure. In the procedure, a column six feet high and six inches in diameter was filled with a stormwater sample. At different time intervals samples were taken from a series of ports located at different heights, and the concentration of particles in each sample was measured. Settling velocity was computed knowing the port height and the time of withdrawal, and the concentrations were used to calculate percentage of particles in the settling velocity range. A visual representation of the process is provided in Figure 2.1.

The NURP settling velocity distribution was computed from both the average of 46 different settling column tests collected during the NURP studies and also data collected by Whipple and Hunter (1981). The USEPA (1986) report makes many observations about the settling velocity distribution of particles from the NURP studies. First, a wide range of particle sizes was observed in the samples. Second, the settling velocity distributions displayed a substantial storm-to-storm variation. Finally, no significant site-to-site variation of settling velocity distribution could be calculated because settling velocity distribution varied greatly at each individual site. A summary of the average settling velocity distribution is provided in Table 2.7. The distribution and corresponding 95 percent confidence interval is provided in Figure 2.2.



O = Data Point - Record % removed based on observed vs. initial concentration

Settling velocity (V_s) for that removal fraction is determined from the corresponding sample depth (h) and time (t)

$$V_s = H/T$$

Observed % removed reflects the fraction with velocities equal or greater than computed V_s

Figure 2.1. Visual representation of method used for NURP distribution (from USEPA 1986).

Table 2.7. Summary of NURP distribution

Size Fraction	% of Particle Mass in Urban Runoff	Average Settling Velocity (ft/hr)	Equivalent Particle Size (μm)*
1	0 – 20 %	0.03	1.7
2	20 – 40%	0.3	5.3
3	40 – 60%	1.5	11.9
4	60 – 80%	7.	25.7
5	80 – 100%	65.	95.6
*Assuming specific gravity of 2.65			

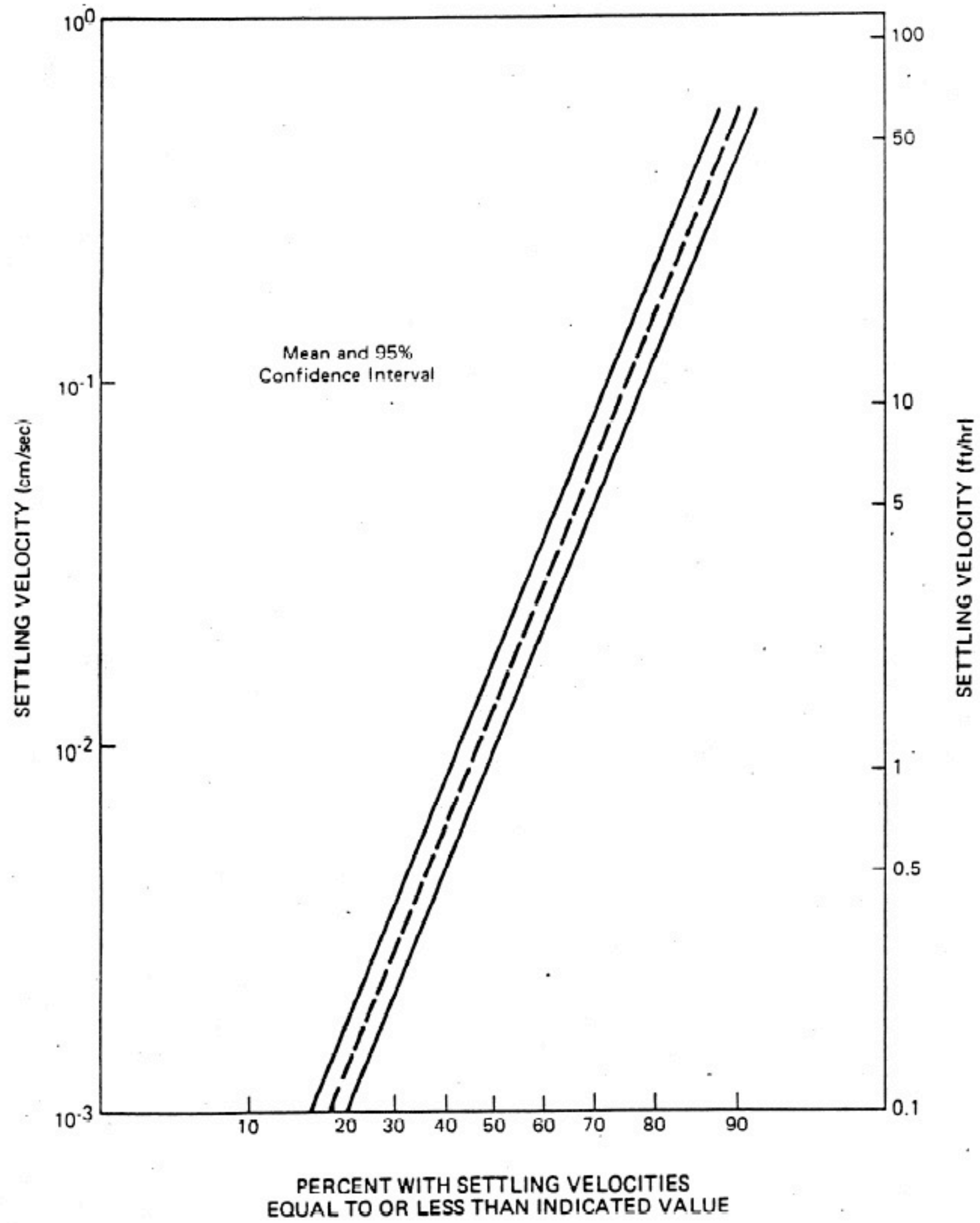


Figure 2.2. NURP distribution with confidence interval (USEPA 1986).

Despite its common use and acceptance, the NURP distribution may not be representative of settling velocity distributions for particles in urban runoff. Particle size distributions vary based on land-use, site location, and storm intensity (Goonetilleke *et al.* 2005, Egodawatta *et al.* 2007), and recent research has found that the NURP distribution, when converted to a particle size distribution assuming a constant density of 2.6, is finer than many distributions measured in urban watersheds. The NURP distribution focuses on suspended solids and does not account for larger particles that would easily settle, which could explain the discrepancy (James 2003). Additionally, the accuracy of the automatic sampling and settling velocity measurement methods used to generate the settling velocity distribution has been questioned (Pisano 1996). The original report acknowledges the data set used to develop the NURP distribution is limited in scope, and the agency encourages expansion of the dataset and development of site-specific estimates (USEPA 1986).

2.4.2. Source Studies

A number of studies have focused on characterizing the particles directly from the surfaces of contributing watersheds. One of the earliest investigations into the pollution impacts of street surface contaminants was commissioned by the USEPA. The study involved collecting particles from street surfaces and analyzing the particles' physical and chemical characteristics (USEPA 1972). During the investigation researchers showed particles on street surfaces are highly contaminated, particles contain mostly inorganic contaminants that are associated with fine solids, and management systems of the era were inadequate (Sartor *et al.* 1974).

Generally, particles are collected using either street sweepers or vacuums. An example of a study collecting samples with street sweepers is that of Viklander (1998). In the study a street sweeper owned by the municipality in Lulea, Sweden was used to sweep one side of a road at various sampling locations. The sediment collected from each site was collected in plastic beakers and subsequently analyzed for size distribution and chemical characteristics. Rather than using samples collected from street sweepers, other researchers have utilized vacuums to collect street surface particles. Lau and Stenstrom (2005) used a Royal Model 4150 vacuum for sample collection at various sites in the City of Santa Monica. This model of vacuum had a rotating brush and was run along street curbs to collect samples. Murakami *et al.* (2005) utilized a different vacuuming approach to collect street sediments in Japan. The researchers first sprayed two liters of deionized water on a gutter surface and then used a Puzzi100 vacuum cleaner to collect the mixture of road dust and water. In both of the studies, particle size distribution and chemical properties of the street surface particles were analyzed.

A list of studies characterizing the size distribution of particles collected directly from street surfaces and the methods used to collect the particles is provided in Table 2.8. The results for d_{50} (i.e. the 50th percentile equivalent particle diameter) from some of the studies are displayed in Figure 2.3. Many of the studies displayed in Figure 2.3 are also compared in a paper written by Kim and Sansalone (2008).

Table 2.8. Studies characterizing the size of street surface particles

Study	***Sampling Method***	***Location***	***PSD Method***
USEPA 1972	Vacuum sweeper	Various cities, street surfaces	Sieved
Ellis and Revit 1982	Point sampling	N.W. London	Dry and wet sieving
Grottker 1987	Vacuum cleaning	Hildesheim, Germany	Dry sieving
Viklander 1998	"Broadway city" street sweeper	northern Sweden, highway	Dry and wet sieving
Sansalone and Tribouillard 1999	Vacuum	I-75, Cincinnati	Air dried, sieved
German and Svensson 2002	Nilfsk WD225F vacuum	Jonkoping, Sweden	Dry sieving
Vaze and Chiew 2004	Vaze and Chiew 2002	Melbourne, Australia street	Dry and wet sieving
Deletic and Orr 2005	Wet vacuuming	Aberdeen, Scotland	Wet Sieving
Lau and Stenstrom 2005	Royal Model 4150 vacuum	Santa Monica, street surfaces	Air dried, sieved
Murakami *et al.* 2005	Puzzi100 vacuum with water	Tokyo streets	Wet sieving
Bathi *et al.* 2009	Manual dipper (creek sediment)	Tuscaloosa and Northport, AL	Oven dried, sieved

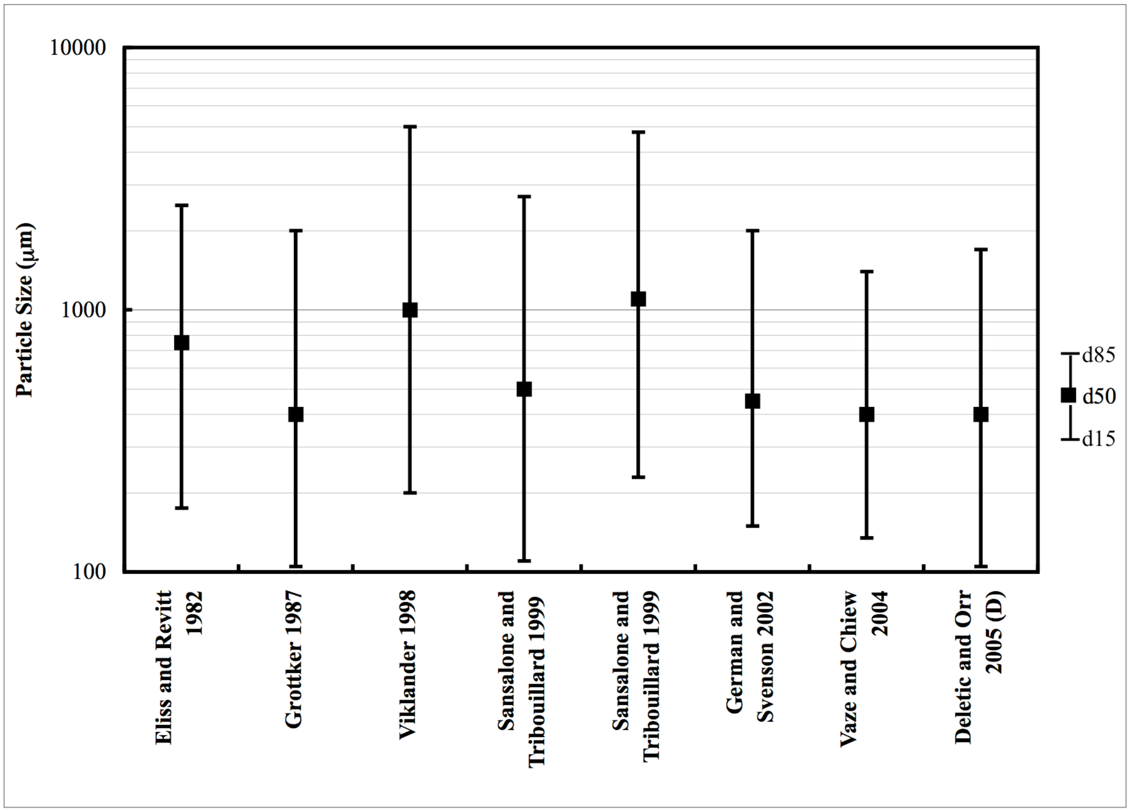


Figure 2.3. Comparison of d_{50} from various source studies.

2.4.3. Runoff Studies

A number of researchers have also used discharge monitoring to analyze the particle size distribution in stormwater runoff. Discharge monitoring is generally conducted by one of three methods: automatic sampling, grab sampling, and collection of lateral pavement sheet flow (LPSF).

An example of automatic sampling is found in Furumai *et al.* (2002), which collected runoff from a highway site at the inlet of a retention basin. An automatic sampler with 24 bottles was calibrated to collect a sample at a flow-weighted interval of 10 cubic-meters. The methods used in the Furumai *et al.* (2002) study are similar to the methods used in other studies utilizing automatic samplers.

Grab sampling can also be conducted to determine characteristics of urban stormwater runoff. A protocol for stormwater grab sample collection is outlined in Li *et al.* (2005). During a rainfall event, researchers collected four-liter grab samples directly from a stormwater outfall. The samples were collected once every fifteen minutes for the first hour, once every hour for the next seven hours, and occasionally thereafter if the storm exceeded eight hours in length. The grab samples were also supplemented with flow weighted composite samples collected by automatic samplers. Samples collected in both studies were analyzed for particle size distribution and pollutants. Results are provided later in the section.

Another method for collecting samples from stormwater runoff involves collecting only the lateral pavement sheet flow (LPSF) from roadways. The method is described in detail by Lin *et al.* (2009), but similar concepts have been used in other studies. In the Lin *et al.* study, LPSF flowed over the roadway surface, entered a collection system, and eventually drained to an 80-liter grit chamber. Water from the grit-chamber then flowed to a 2200-liter settling basin. Particles in the settling basin were allowed to settle for two days, and the supernatant was then siphoned off. Solids from the grit chamber and the slurry from the settling tanks were collected separately, and particulate matter in the samples was oven dried. The particle size distributions of particles collected from both the grit chamber and the settling tank were subsequently measured.

A number of studies have used the various collection methods and measurement methods to determine particle size distribution in runoff. Table 2.9 lists some of the studies, and it includes information about sampling methods and particle size distribution measurement. Figure 2.4 compares the d_{50} of the particle size distributions from some of these studies.

Table 2.9. Runoff studies characterizing particle size distribution

Study	***Sampling Method***	***Location***	***PSD measure***
Whipple & Hunter 1981	Unstated, composted	New Jersey	Settling column
Lygren *et al.* 1984	Collection trap	Jessheim, Norway highway	Sedimentation Column
Sansalone *et al.* 1997	LPSF	I-75 Cincinnati	Oven dried, sieved
Sansalone *et al.* 1998	LPSF	I-75 Cincinnati	Sieving
Andral *et al.* 1999	Channel and sampling	A9 motorway	Laser, velocity
Legret & Pagotto 1999	Automatic sampler	France, roadway	Sieving (>500um), laser
Drapper *et al.* 2000	Grab samplers (first 20L)	Queensland, Australia	Mastersize S Laser (<710um)
Furumai *et al.* 2002	Automatic sampler	Winterthur, Switzerland inlet	Stepwise filtration
Li *et al.* 2005	Grab and automatic samples	Los Angeles roads	AccuSizer 780
Westerlund & Vicklander 2005	Unstated	Sweden, roadway	Coulter counter (4 to 120 um)
Anta *et al.* 2006	Sigma 900 automatic sampler	Santiago de Compostela	Laser
Li *et al.* 2006	Grab samples	West L.A. highway sites	Settling
Kayhanian *et al.* 2008	Grab Samples	Parking lots, highways	LISST, Sieving
Sansalone & Kim 2008	Free-fall grab samples (12L, 1L)	Baton Rouge, LA	Wet sieving
Lin *et al.* 2009	PM mass	City Lake Park, I-10	Imhoff cone, sieve
Sansalone *et al.* 2009	Manual recovery	Baton Rouge, LA lake watershed	Settling column

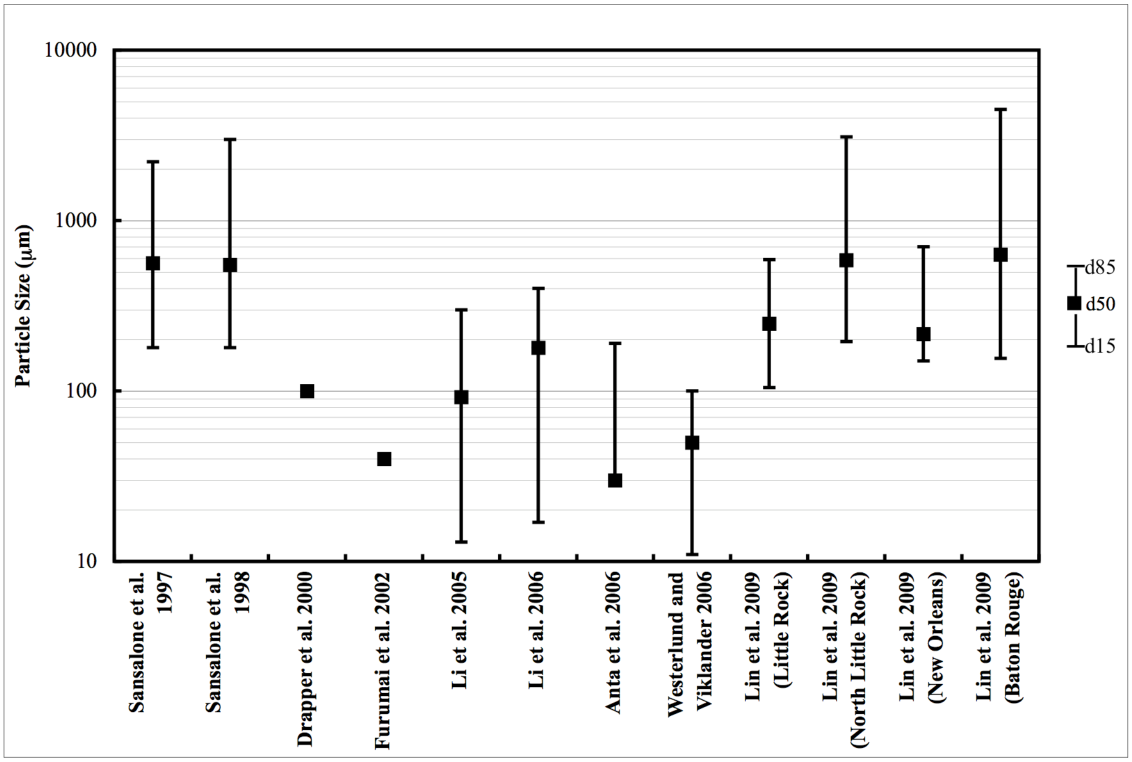


Figure 2.4. Comparison of d_{50} from various runoff studies (Note: Information about d15 and d80 was not available for the points without bars).

Particle size distributions from different studies can vary by up to one and a half orders of magnitude. The relationship can be seen in Figure 2.5, which is taken from Walker and Wong (1999) and directly compares particle size distributions from a variety of studies. Similarly, published distributions from urban stormwater runoff approximately fall between two distributions: the NURP distribution and the distributions characterized by collecting LPSF. Figure 2.6 compares the NURP distribution (USEPA 1986), a distribution from a LPSF study (Sansalone *et al.* 1998), and an intermediate distribution characterized by Li *et al.* 2005.

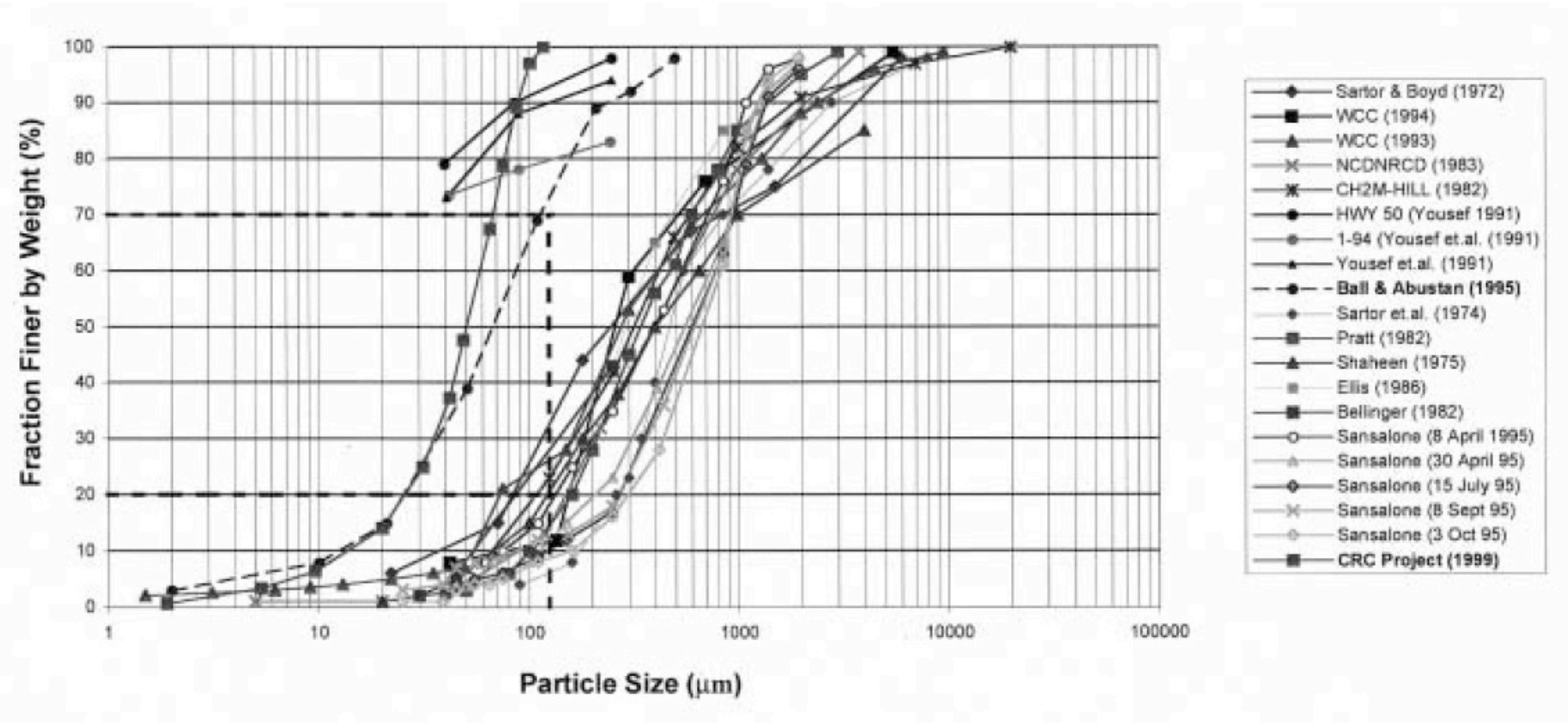


Figure 2.5. Comparison of particle size distributions from runoff studies (from Walker & Wong 1999).

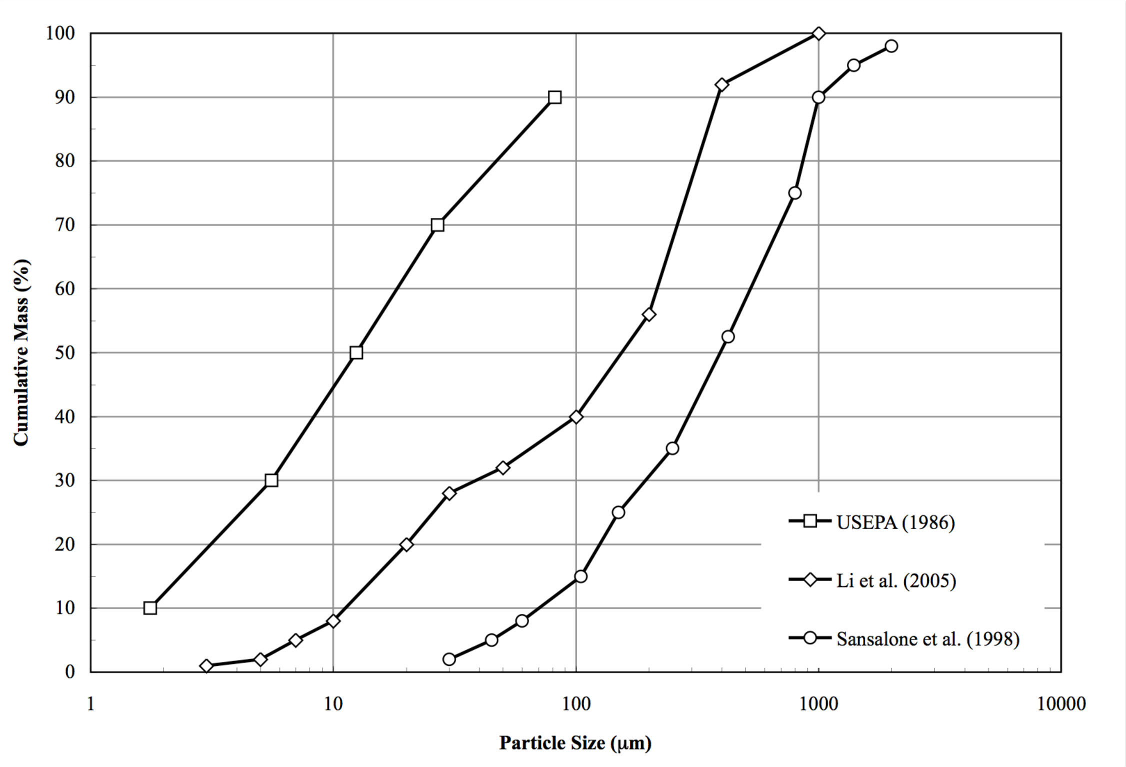


Figure 2.6. Range of particle size distributions found in urban runoff.

Storm characteristics may have an impact on the availability of pollutants to be mobilized in runoff. Specifically, Egodawatta *et al.* (2007) used simulated runoff on urban road surfaces to demonstrate the impact of rainfall intensity and duration on the fraction of particles washed off a road surface. The researchers found an increase in rainfall intensity and rainfall duration resulted in an increase in the fraction of particles washed off roadway surfaces. The results are demonstrated in Figure 2.7, which shows the results of the experiments from one of the urban roadway sites. In the figure "Fraction Wash-off" is defined as the mass of particulates removed from the road surface divided by the total mass of particles on the road surface. The researchers also made observations about particle size distribution and wash-off potential. While the originally available particles on the road surfaces had a d_{50} of 100-150 micrometers, the d_{50} of the particles washed-off for rainfall intensities between 40 and 90 mm/hr was 50-100 micrometers. The difference in d_{50} indicates the experimental rainfall intensities were more effective at mobilizing the smaller (<100 μm) particles rather than larger (>100μm) particles.

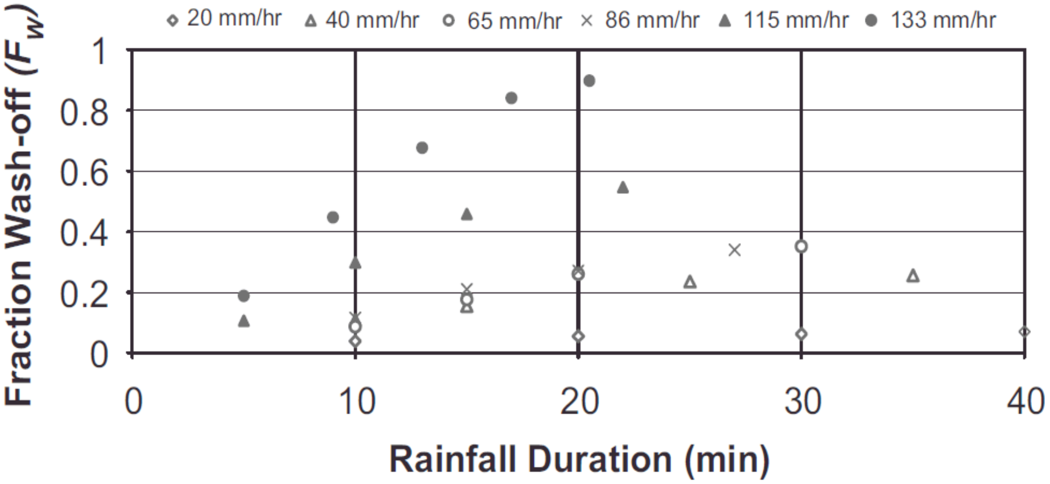


Figure 2.7. Particle wash-off compared to rainfall duration and intensity (from Egodawatta *et al.* 2007).

Many studies measure storm characteristics and particle size distributions concurrently, but the relationship observed by Egodawatta *et al.* (2007) has not always been observed. Table 2.10, which shows results from two studies, compares the d_{50} of suspended solids collected from various runoff events and corresponding storm characteristics. Storm characteristics in the table include antecedent dry period (ADP), storm duration, rainfall depth, and total rainfall volume. As indicated in the table, a clear relationship between d_{50} and rainfall intensity or duration cannot be established. The main difference between the studies listed in the table and the Egodawatta *et al.* (2007) study is the method of collection. The former studies collected particles during actual storms, while the latter study utilized synthetic rainfall on highly controlled study plots. The relationship among particle mobilization, particle transport, storm characteristics, traffic characteristics, and other physical processes incorporated in the Li *et al.* (2005) and Sansalone *et al.* (1998) studies is complex and interconnected so developing a clear relationship only between storm characteristics and particle size distribution at an outfall is not feasible.

Table 2.10. Particle size and storm properties

Study	Date	d_{50} (mm)	ADP (day)	Dur. (hr)	Depth (mm)	Avg. Intensity (mm/hr)	Max. Intensity (mm/hr)
Li *et al.* 2005	15-Dec-02	28	16.1	3.33	2.5	0.75	2
	7-Nov-02	80	40.2	46.5	71.4	1.54	12.2
	29-Nov-02	80	20.2	7.75	1.8	0.23	3.1
	7-Nov-02	180	40.1	47.5	29	0.61	10.2
Sansalone *et al.* 1998	21-May-96	450	5.3	0.58	1	1.71	19
	18-Jun-96	465	3.0	1.05	11.3	10.76	55
	7-Jul-96	785	4.9	0.83	40.4	48.48	120
	8-Aug-96	585	9.0	0.85	14.1	16.59	110
	17-Oct-96	690	7.6	10.27	29.1	2.83	19

2.5. Importance of Particle Size and Settling Velocity

As described in the previous section, particle size distribution and ultimately settling velocity vary among many studies. The discrepancies can have a large impact on the performance of various stormwater treatment practices. The following section investigates the impact of particle size on traditional settling ponds and newer proprietary devices. Removal of metals adsorbed to particles is also investigated.

2.5.1. Dry Detention Ponds

Detention ponds are a commonly used stormwater management practice and depend almost entirely on sedimentation for solids and pollutant removal. The ponds operate by maintaining a specific overflow velocity (inflow/area) for a given flow rate. Particles with a settling velocity greater than the overflow rate will be retained in the pond, and particles with a settling velocity less than the overflow rate may be flushed through the pond. Percent removal in settling ponds is a function of pond size, incoming flow rate, and mixing conditions. Fully mixed and fully quiescent with plug flow operating conditions represent the minimum and maximum percent removal, respectively. For ponds with constant cross-sectional area, Equation 2.4 provides percent removal for fully mixed conditions. Equation 2.5 provides percent removal for fully quiescent plug flow.

$$\frac{C}{C_o} = 1 - EXP\left[\frac{-wA}{Q}\right]$$ Equation 2.4

$$\frac{C}{C_o} = \frac{wA}{Q} \leq 1$$ Equation 2.5

where:

Q: Volumetric inflow
A: Area of pond
C: Concentration of sediment captured
C/C_o: Percent removal (%)

2.5.2. Hydrodynamic Separators

Proprietary underground devices known as hydrodynamic separators are used in urban areas for stormwater treatment. Hydrodynamic separators remove particles by providing enhanced gravitational sedimentation. The enhanced sedimentation is achieved by providing centripetal forces caused by a swirling action of the fluid created by the configuration of the inlets. Wilson *et al.* (2008) analyzed various hydrodynamic separators to determine the percent removal as a function of flow rate, particle settling velocity, and device properties. The researchers used dimensional analysis to combine the parameters into an equation for the dimensionless Peclet number (Equation 2.6), which represents the ratio of advection to diffusion. The Peclet number was then used to develop an empirical equation for removal efficiency shown in Equation 2.7.

$$Pe = \frac{whd}{Q}$$ Equation 2.6

where:

Pe: Peclet number
h: Settling depth
d: Device diameter
Q: Discharge into device

$$\eta = \left(\frac{1}{R^b} + \frac{1}{(aPe)^b} \right)^{-1/b}$$ Equation 2.7

where:

η: Removal efficiency
R, b, a: Empirical coefficients

2.5.3. Metal Adsorption and Removal

Sansalone and Buchberger (1997) used the samples collected from Interstate 75 to calculate the effect of particle size on adsorbed metal concentration. The concentrations of zinc, copper, and lead decreased as particle size increased. The trend, however, was not apparent for cadmium (Sansalone & Buchberger, 1997). Average concentrations of four metals determined from five rainfall events are shown in Table 2.11. The average concentrations for particle sizes and particle size distributions are used to calculate the percent of adsorbed metals removed for detention ponds and hydrodynamic separators.

Table 2.11. Average concentration of adsorbed metals in stormwater (Sansalone & Buchberger, 1997)

Particle Size (μm)	**Zn Conc. (μg/g)**	**Pb Conc. (μg/g)**	**Cd Conc. (μg/g)**	**Cu Conc. (μg/g)**
4750-9500	35.8	8.6	19.9	14
2000-4750	104.8	59.2	15.0	14
850-2000	219.6	44.0	10.8	46
425 – 800	302.0	56.4	9.7	209
250 – 425	313.6	82.8	8.1	121
150 – 250	592.6	187.4	9.4	217
75 – 150	1141.4	332.4	14.9	323
63 – 75	1289.8	311.2	16.4	374
45 – 63	1206.6	325.8	17.0	394
38 – 45	1325.8	290.8	17.1	398
25 – 38	1409.6	303.2	16.7	478

2.5.4. Calculations for Impact of PSD on Stormwater Unit Operation Removal

To demonstrate the importance of particle size distribution to best management practice performance, removals for the NURP, Li *et al.* (2005), and Sansalone *et al.* (1998) distributions were compared. The Sansalone *et al.* (1998) distribution is orders of magnitude coarser than the NURP distribution, and the Li *et al.* (2005) distribution falls between the two distributions. A comparison of the distributions is provided in Figure 2.6. The coarser Sansalone *et al.* (1998) and Li *et al.* (2005) distributions are consistent with the particle size distributions of urban stormwater measured in other studies (Walker & Wong, 1999). For purposes of comparison, the NURP settling velocity distribution is converted to a particle size distribution assuming Stokes' law for smooth spheres.

To compute suspended solids removal for the NURP distribution, the direct settling velocity distribution from the NURP study is used. For the Sansalone *et al.* (1998) and Li *et al.* (2005) distributions, settling velocity distribution is calculated using the Ferguson and Church equation described previously. The particles are assumed to be intermediate grains characterized by sieve diameters. Suspended solids removal from detention ponds for fully turbulent and fully quiescent conditions is calculated using Equation 2.4, Equation 2.5, and the settling velocity distribution. Inflow into the pond is determined as the flow generated by the maximum intensity of 3-month, 24-hour storm for Minneapolis, MN falling on a completely impervious surface. The depth for this storm is 1.45 inches (Huff & Angel 1992), and a maximum intensity of 0.616 inches/hour is calculated using the SRS Type II storm distribution. Results for a theoretical detention pond operating under fully mixed and fully quiescent conditions are presented in Figure 2.8.

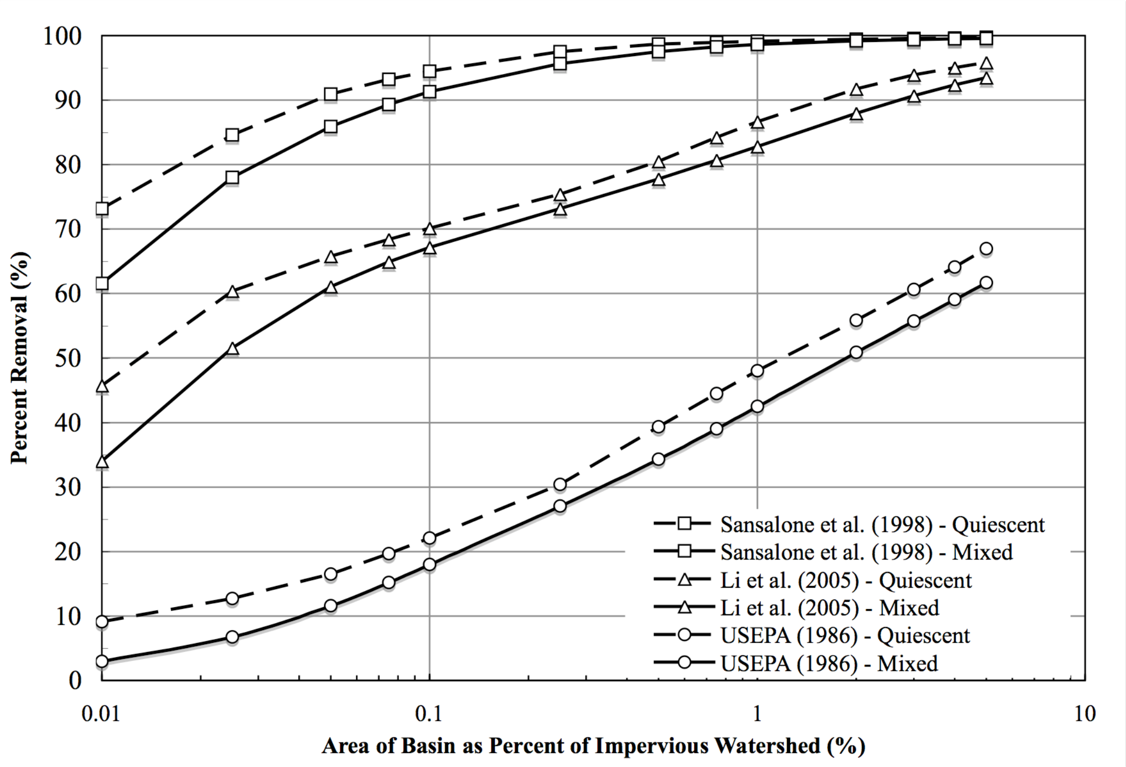


Figure 2.8. Estimated percent solids removal for detention ponds.

Solids removal from hydrodynamic separators is calculated using Equation 2.7 for a hydrodynamic separator with a maximum flow of 1.5 ft^3/s. The maximum flow rate is achieved if the runoff from a 2.4 acre impervious watershed subjected to the maximum intensity from above is routed directly to the device. For the calculations, the following empirical coefficients were used: R = 0.98, b = 2.28, a = 0.70. Results are displayed in Figure 2.9.

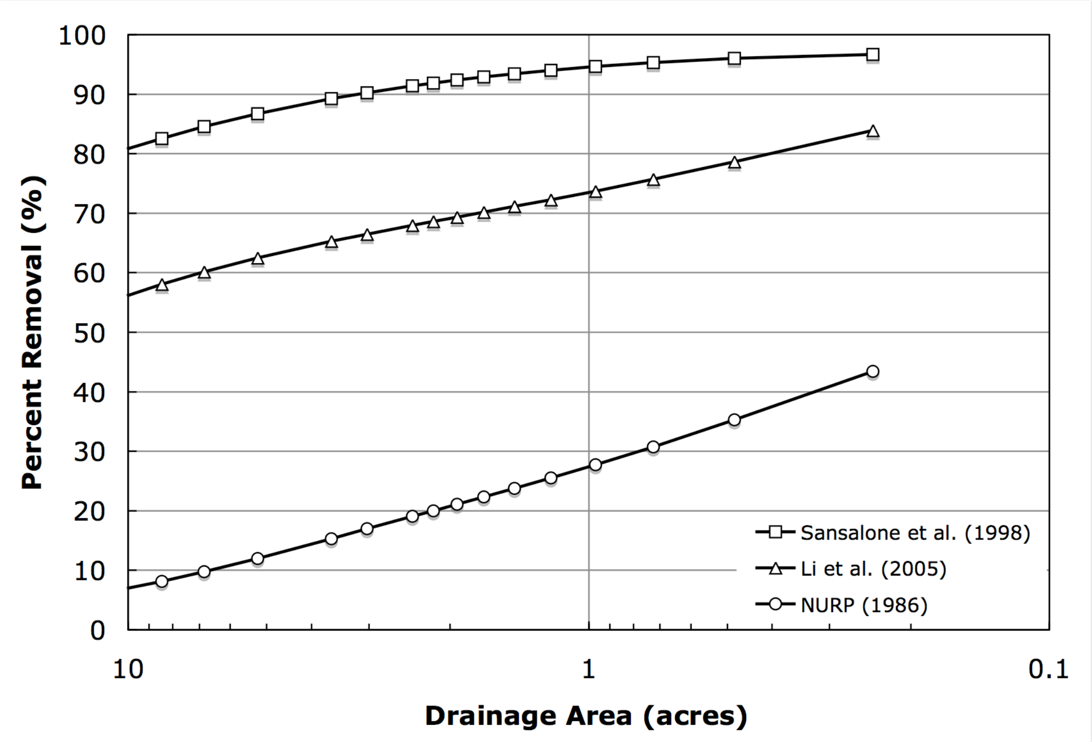


Figure 2.9. Estimated percent solids removal for hydrodynamic separators.

The removal of heavy metals was computed for the Sansalone *et al.* (1998) distribution. Two different relationships for adsorbed metal concentration versus size are used. First, relative metal concentrations are correlated to their respective particle sizes using the data collected by Sansalone and Buchberger (1997). For comparison metal concentrations are correlated to the respective particle sizes assuming the particles are smooth spheres and the adsorbed metal concentration and specific surface area of spheres are proportional. Once the metal concentrations are correlated to the particle sizes, removal is computed using the same methods described for removal of suspended solids in stormwater. Results for expected metals removal are provided in Table 2.12.

Table 2.12. Metals removal for Sansalone *et al.* (1998) distribution

Pollutant	Detention Pond Percent Removal (A_{pond} = 0.1%*A_{basin})	Hydrodynamic Separator Percent Removal (Inflow = 50%*Max_Flow)
TSS	91.34	92.4
Zn	78.58	84.1
Pb	79.34	85.2
Cd	87.43	89.8
Cu	81.57	85.7

2.5.5. Summary of Particle Size Distribution Effects

As demonstrated, the assumed particle size distribution has an impact on the estimated removal from both settling ponds and hydrodynamic separators. Additionally, assumptions about particle shape have an impact on predicted metals removal. The results have important results with regards to percent solids removal, percent metals removal, and cost and maintenance considerations for the devices.

2.5.5.1. Percent solids removal

As shown in Figures 2.8 and 2.9, stormwater management practices utilizing settling as their primary removal mechanism can remove a greater percentage of solids for coarser particle size distributions. Two conclusions can be drawn from this analysis. First, if a pond is sized assuming the NURP distribution but the actual distribution from the watershed is coarser, the pond will remove a higher percentage of solids than expected. As a result, the actual downstream solids concentration will be smaller, the effluent solids load will be smaller, and the expected solids collection within the pond will be greater than expected. Similarly, hydrodynamic separators provide minimal treatment for fine particle size distributions such as the NURP distribution, but they can remove over 90 percent of total solids if a coarser particle size distribution, such as the Sansalone *et al.* (1998) distribution, is assumed.

Second, a pond designed for a specific solids removal will require a small surface area for a coarser particle size distribution as compared to the NURP distribution. As shown in Figure 2.8, the area for a pond to achieve 50 percent removal is approximately 1.5 percent of the watershed area assuming a NURP distribution. If the pond is designed assuming the Li *et al.* (2005) distribution, the pond would only have to be approximately 0.01 percent of the watershed area, which means the pond could be over 150 times smaller. The specific results are only valid for a storm intensity of 0.616 in/hr. Nonetheless, stormwater ponds designed for a coarser particle size distribution will require less area and cost less to construct.

2.5.5.2. Metals removal

The percent of total adsorbed metals removed is smaller than the total percent of solids removed, as shown in Table 2.12. In stormwater management practices relying on sedimentation, large particles are removed more quickly and more effectively than small particles. The amount of total adsorbed metals that passes through the stormwater management practice is associated with the total solids that also pass through the stormwater management practice. Therefore, total adsorbed metal removal is less than total solids removal because more metals are adsorbed to small particles as compared to large particles. A substantial portion of adsorbed metals, however, is removed by sedimentation of large particles, as shown in Table 2.11. It is important to note the values listed in Table 2.11 only represent the removal of adsorbed metals. Stormwater management practices relying only on sedimentation have no mechanism to remove dissolved metal ions.

2.5.5.3. Cost and Maintenance Considerations

The concepts presented in this section have an impact on BMP design, cost, and maintenance. A pond designed for a coarser distribution is substantially smaller than a pond designed for the NURP distribution. Smaller ponds cost less to install and require a smaller land area. Maintenance, however, is also impacted by pond size. As solids removed from stormwater accumulate in ponds, the effective volume of the pond decreases. As the design volume of the pond decreases, the impact of accumulated sediment relative to the total pond volume increases. To sustain an effective pond volume, the solids collected at the bottom of the pond would have to be removed more frequently for a smaller pond.

The results of this distribution analysis could also have an impact on stormwater management practice design and cost for hydrodynamic separators. As shown in Figure 2.9, hydrodynamic separators can remove up to 90 percent of total solids for coarse distributions. Instead of installing large stormwater management practices for watersheds generating coarse particle size distributions, a hydrodynamic separator could be implemented as the primary solids treatment practice. The money saved could be utilized to install more advanced treatment methods targeting dissolved pollutants. Similar to ponds, however, accumulated sediment must be removed from hydrodynamic separators to maintain effectiveness.

2.5.5.4. Other Considerations

Although the NURP distribution may not accurately characterize the particle size distribution in some locations, it does provide a conservative estimate for stormwater management practice design. If the assumed distribution is coarser than the actual distribution, the device will remove fewer solids than expected. Additionally, many recent particle size distributions have been characterized using mechanical sieving and sophisticated particle sizing instruments. The methods provide an accurate representation of particle size, but they do not provide detail about particle density or particle shape. If density and shape are not considered in the calculation of settling velocity, actual removal could be more or less than predicted. Therefore, appropriate assumptions about shape and density and appropriate equations should be utilized when calculating percent removals. Tests in settling columns should also be utilized to verify the settling velocity predicted by equations based on particle size.

The results presented only compare three distributions, but particle size distribution in stormwater runoff depends on many factors. For example, particle size distribution will vary with site location (spatially), with rainfall intensity (hydrologically), and with season or antecedent dry period (temporally). Upstream treatment devices and conveyance systems also have an impact on particle size distribution leaving a watershed. The distribution characterized by Sansalone *et al.* (1998) collected runoff directly from a roadway surface, and the particle size distribution would likely be different if the runoff were routed through pipes or upstream treatment devices. As a result, the particle size distribution or the settling velocity distribution of particles in urban stormwater runoff should be determined for specific sites under different storm conditions to ensure the most accurate design.

3. Existing Elutriation Devices

As demonstrated in the previous chapter, particle settling velocity distribution are important parameters to consider when designing stormwater management practices. A variety of methods have been utilized to directly measure settling velocity of particles in stormwater. Elutriation devices use an upward flow of water through a series of columns to separate particles into various settling velocity ranges. In the following sections existing elutriation devices are examined and experiments conducted on one of the existing devices is described.

3.1. General Operation of Elutriation Devices

Elutriation by water is based on separation of particles by rising water currents flowing upward through a series of columns. First, a suspension of particles is introduced to the upward flow currents. A particle will not flow upward through the column if it has a settling velocity greater than the upward velocity of the rising currents. Conversely, the particle will rise with the currents if it has a settling velocity less than the upward velocity of the flow. Water elutriation to determine a settling velocity distribution is carried out with a series of columns with increasing diameters. A suspension of particles flows through the series of columns at a constant flow rate maintained by either a constant head apparatus or a pump. The upward velocity in the column decreases as column diameter increases. After a period of time, the particles in the suspension are retained in the various columns based on their setting velocities. The upward velocity and mass retained in each column is determined, and the settling velocity distribution is generated.

Columns for elutriation devices used in previous studies have been made from glass and are pear-shaped, as shown in Figure 3.1. The suspension of particles is delivered at a constant flow rate by a long, rigid, narrow tube that extends to the bottom of the column. The suspension of water and particles exits the column through another short, narrow, rigid tube. A rubber stopper is inserted at an opening at the top of the column to hold the tubes in place and to establish an airtight seal. The series of columns is connected using flexible plastic tubing attached to the inlet and outlet tubes.

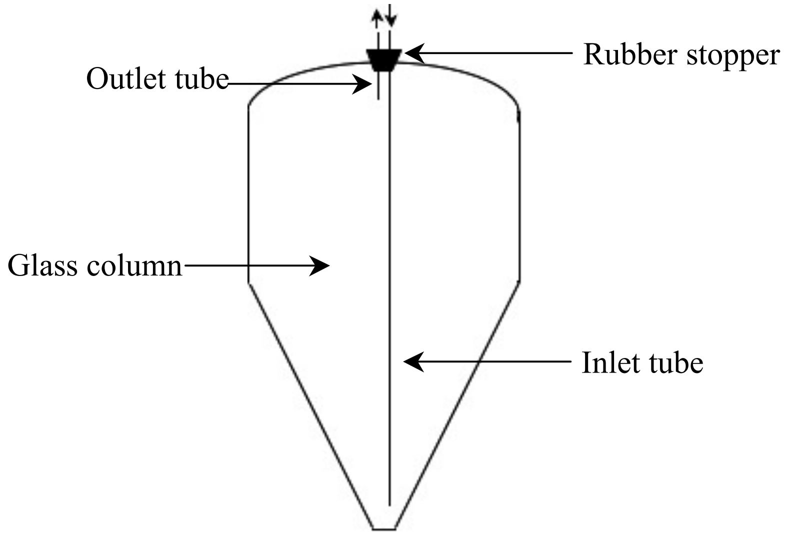


Figure 3.1. Typical settling column for elutriation device.

3.2. Applications of Elutriation Devices

The effectiveness of elutriation devices to accurately separate particles based on settling velocity has been documented. Follmer and Beavers (1973) used an elutriation device consisting of three glass columns to separate particles into four settling velocity classes. A mass balance showed nearly all of the mass input into the system was recovered after the elutriation device was operated. Additionally, Follmer and Beavers showed the elutriation device provided reproducible results and required little operator attention. They were unable to determine if the measured settling velocity distribution was accurate, however. Muller and Tisue (1977) investigated the effectiveness of a similar elutriation device by running a sample through the elutriation device, measuring the particle size distribution in each column, and comparing the measured particle sizes in each column to the expected particle sizes in each column. The researchers found an acceptable match between the actual size distribution in each column and the expected size distribution. The research demonstrates elutriation devices can effectively separate particles into unique ranges.

Walling and Woodward (1993) used an elutriation device similar in design to the devices tested by Follmer and Beavers (1973) and Muller and Tisue (1977) to measure the settling velocity distribution of sediments from the Exe River in Devon, U.K. The device consisted of four glass columns to separate sediment with equivalent spherical diameters of >63 μm, 63-32 μm, 32-16 μm, 16-8 μm, and <8μm. The suspension was introduced to the device by placing a tube in the river, and the river's water was pumped through the system by a pump located downstream of the columns. The device was placed on the shoreline in a protective box, and it was operated for up to nine hours at a flow rate of 0.1 L/min. Walling and Woodward calculated a particle size distribution from the settling velocity distribution, and found it was coarser than the particle size distribution measured using laser diffraction.

Marsalek *et al.* (2006) adapted the Walling and Woodward (1993) device to measure the settling velocity of solids in combined sewer overflows (CSOs). Two major modifications were made to the device: the flow was increased from 0.1 L/min to 0.5 L/min to ensure turbulent flow conditions in the tubes connecting the columns, and the number of columns was increased from four to eight to get a more refined settling velocity distribution. Settling velocity distributions were generated from operation of the elutriation device, but the researchers described concerns with the operation of the device. First, the device required a CSO sample of 60 liters to ensure accurate results. Such a large volume of CSO influent is difficult to collect and transport. Most notably, the device was identified as being more difficult to operate than the UFT column, which also characterizes settling velocity distribution.

3.3. Environment Canada Portable Elutriation Device

To compliment the work with their existing elutriation devices, researchers at Environment Canada who worked on the Marsalek *et al.* (2006) study developed a portable elutriation device. The University of Minnesota approached Environment Canada with interest in testing the portable elutriation device, and Environment Canada temporarily loaned the device so performance tests could be conducted. The device consists of eight glass columns of increasing diameter, which were housed in a protective case. The diameters of the columns were 25, 34, 49, 70, 105, 143, 197, and 197 mm. The case containing the columns attached to a specially constructed aluminum table. The device screwed directly into the table for stability, and a vertical truss on the table secured two mixers. A picture of the device is provided in Figure 3.2.

Figure 3.2. Portable elutriation device developed by Environment Canada.

3.3.1. Experimental Setup for Testing Environment Canada Device

The portable elutriation device (hereafter referred to as the Environment Canada device) contained the glass columns, a pump, and two mixers. Before the device could be operated, researchers at the University of Minnesota had to install various components, which are shown in Figure 3.3. First, rigid plastic tubing with ¼-inch (6.3 mm) inner diameter (1) was used for the tubes entering and exiting the columns. The rigid plastic tubing was inserted in rubber stoppers (2), and the rubber stoppers were placed at the opening of each of the columns. Flexible latex tubing was used to connect the plastic tubing (3). Finally, larger diameter latex tubing (4) was installed at the bottom opening of each column. Plastic clips (5) were used to keep this tubing folded over to prevent leaking.

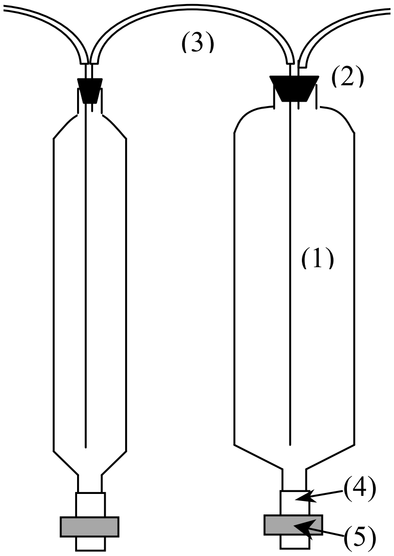


Figure 3.3. Column setup for Environment Canada device.

Six of the eight columns in the portable elutriation device were connected in this manner. The 25 mm column was not used because it made the device difficult to operate, which is described later. The extra 197 mm column was intended to be used to capture particles with a density less than water, and this application was not required for the testing. A long piece of the smaller diameter latex tubing was connected to the 34 mm column, and another piece of the latex tubing connected the 197 mm column to the pump.

3.3.2. Operation of the Environment Canada Device

To test the elutriation device, a mixture of sieved ground silica was used. Ninety percent of the mixture was ground silica sieved between 44 and 88 micrometers, 5 percent was ground silica sieved between 88 and 125 micrometers, and 5 percent was ground silica sieved percent between 125 and 240 micrometers. Although the silica in the study was dry sieved, many particles smaller than 44 micrometers remained in the mixture.

Before the device could be operated, the six columns were filled with tap water, and the rubber stoppers were firmly placed on the tops of each of the columns. The latex tube connected to the first column in the device (the 34 mm column) was submerged in a bucket of clean tap water, and the pump was switched on. Since the pump was located downstream of the device, it relied on suction to pull water through the system. The device was operated for 10 minutes with clean water to ensure the system did not have any air leaks that would affect the operation of the device.

Once the device was tested for air leaks, the pump was turned off. A mass of the ground silica mixture ranging between 7.5 and 10 grams was suspended in 20 liters of tap water, and the suspension was continuously mixed using automatic mixers provided by Environment Canada. Three 30-milliliter grab samples of the influent mixture were collected for particle size analysis. The tube connected to the 34 mm column was submerged in the suspension, and the device pump was turned on. When the bucket containing the sediment mixture emptied, it was filled with 20 liters of clean tap water. Addition of the clean water increased the amount of time for particles to be flushed through the system. Operation of the device was considered complete when the entire volume of clean water had entered the system. At five-minute intervals throughout the test, the flow rate was determined by measuring the amount of time required to fill a 500 milliliter beaker.

3.3.3. Experimental Measurement Methodology

After the operation of the Environment Canada device was completed, particles in the columns had to be collected and analyzed. Analysis consisted of measuring mass retained in each column and measuring the particle size distribution of sediments collected in each column.

3.3.3.1. Sample collection

When the test was completed, each of the columns was emptied into clean containers. The 34, 49, and 70 mm columns were emptied into glass beakers ranging in volume from one to two liters. Water and sediment was collected in a four liter plastic bucket for the 105 mm column, an eight liter bucket for the 143 mm column, and a twenty liter bucket for the 197 mm column. During the collection process the sides of the columns were rinsed to ensure the entire sample was collected. Water and sediment from the effluent of the device was collected in two twenty-liter buckets and combined to form one composite sample.

3.3.3.2. Mass determination

The mass of sediment retained in each column was determined using one of two methods depending on the size of the column. For the 34, 49, and 70 mm columns, the mass retained was determined using the suspended solids concentration (SSC) method outlined by ASTM Standard Test Methods for Determining Sediment Concentration in Water Samples (D 3977-97). Mass for the SSC method was calculated by filtering the entire sample through a 0.45-micron filter, drying the filter and sediment, and determining the mass retained on the filter. The mass of particles retained in the largest columns and the effluent was determined using the TSS method described by APHA Standard Method for Total Suspended Solids Dried at 103-105^{O}C (APHA 2540D). For each column, three 300 milliliter samples were collected using a 100 milliliter wide-bore volumetric pipette. The suspension of particles was continuously mixed by the mixers operating at 300 revolutions per minute (rpm) during sampling. Each sample was then filtered through a 0.45-micron filter, the filter was dried for one and a half hours in an oven at 100 degrees centigrade, and the sediment concentration of the sample was calculated by dividing the sample mass by the sample volume. Finally, the total mass retained in each column was calculated by multiplying the average concentration by the total volume of water in each column.

The SSC method for the first three columns was justified for two reasons. First, the volumes of water in the first three columns were all less than four liters, which allowed for fast and simple filtering. Filtering greater than four liters of suspension is time consuming and requires multiple filters. Additionally, tests of the TSS methods indicated the method was not accurate in representing the larger particles retained in the smallest columns. The TSS methods were accurate for ground silica particles less than 88 micrometers, but the method did not provide an adequate representation of the sediment concentration for particles larger than 88 micrometers. Results of the tests are shown in Table 3.1. The results are consistent with other studies that have shown the TSS method should only be used for silica particles less than 100 micrometers because the method does not account for larger particles (Qizhong 2006).

Table 3.1. TSS tests for various sizes of ground silica

Particle Sizes (μm)	**Mixing Method**	**Conc. Expected (mg/L)**	**Conc. Measured (mg/L)**	**Percent Difference (%)**
44-88	Paddle Mixer, 400 rpm	218	206.4	5.3
44-88	Paddle Mixer, 600 rpm	218	202.5	7.1
88-125	Paddle Mixer, 400 rpm	501	312.9	37.6
88-125	Long Magnetic Stirrer	501	421.2	16.0

3.3.3.3. Particle size distribution measurement

Along with mass retained in each column, particle size distribution was measured for the sediment retained in each column and in the effluent.

Samples for particle size distribution analysis were collected in two ways. For the smallest three columns, the entire sediment mass was collected from the dried samples used in the SSC analysis. For the three largest columns and the effluent, three 30-milliliter grab samples were taken from each of the buckets containing the well-mixed sediment. The respective samples were utilized to measure particle size distribution.

The particle size distribution of each of the samples was measured using a Beckman Coulter Multisizer 3 Coulter Counter. The Multisizer 3 uses electric resistivity to determine the volume of particles passing through a testing orifice. When a particle is pulled through the orifice, an electric pulse is generated. The pulse is then converted to determine volume of the particle, and the volume of the particle is converted to an equivalent spherical diameter. Data is reported as total number counts for 256 different size bins. As the device measures the particle size distribution, large particles in the sample are suspended using a paddle mixer on the device.

Since the device operates with electric resistivity, samples have to be mixed with an ionic solution before measurement. The grab samples from the three longest columns were each mixed with 100 milliliters of Isoton II, the ionic solution, before being analyzed by the Multisizer 3. The sediment samples from the smallest three columns required extra preparation. The entire mass retained in each of the smallest columns was mixed with 1 liter of tap water. The mixture was fully combined using simple inversion (gently turning a bottle from top to bottom) a total of twelve times. Simple inversion has been shown to be a reasonable way to mix samples (Li *et al.* 2005). After mixing, 25 milliliters of the mixture was combined with 100 milliliters of the ionic solution.

Samples were measured using both 100 μm and 400 μm aperture tubes. The device is able to measure particles between 2 and 60 percent of the opening of the aperture tube. The results of the two aperture tubes can be combined to form a smooth distribution. For the tests on the Environment Canada device, the size distributions of particles retained in each column were measured between a range of 2 and 240 micrometers.

3.3.4. Theoretical Performance of Environment Canada Device

To verify the results of the experiments, theoretical models were developed for two scenarios. The first scenario assumed each column had a uniform velocity distribution across the entire cross-sectional area of the column. The second scenario assumed the columns had a laminar velocity profile across the area of the column. The theories are presented below.

3.3.4.1. Uniform flow profile

The uniform flow profile assumption is the simplest assumption that can be made for the elutriation device. Since the diameter of the column and the diameter of the tube extending down the height of the column can be measured, the cross-sectional area can be calculated using Equation 3.1. The average upward velocity in the column can be determined by dividing the flow rate by cross-sectional area as shown in Equation 3.2.

$$A = \frac{\pi\left(d_{column}^{2} - d_{tube}^{2}\right)}{4} \qquad \text{Equation 3.1}$$

where:

A = cross-sectional area
d_{column} = inner diameter of elutriation column
d_{tube} = outer diameter of deliver tube

$$v_{upward} = \frac{Q}{A} \qquad \text{Equation 3.2}$$

where:

v_{upward} = upward velocity in column
Q = flow rate through column

3.3.4.2. Laminar flow profile

Laminar flow conditions occur when the Reynolds number, as described in Equation 3.3, is less than 2300 (Mays 2005). Table 3.2 shows the Reynolds number for each of the columns in the device. The Reynolds number for every column is much less than 2300 so it is reasonable to assume the flow in the columns is laminar. The table also shows the length required for laminar flow to fully develop as well as the length of each column. The development length can be calculated using Equation 3.4.

$$\mathrm{Re} = \frac{D_h v}{\nu} = \frac{2\left(r_{column} - r_{tube}\right) * Q}{\nu * \pi * \left(r_{column}{}^2 - r_{tube}{}^2\right)} \qquad \text{Equation 3.3}$$

where:

Re = Reynolds number
D_h = hydraulic diameter
v = velocity
ν = kinematic viscosity
r_{column} = radius of column
r_{tube} = radius of tube

$$l_d = 0.06 * \mathrm{Re} * d_{column} \qquad \text{Equation 3.4}$$

where:

l_d = Development length

Table 3.2. Reynolds number and development length for columns

Column Number	***Column Diameter (mm)***	**Hydraulic Diameter (mm)**	***Reynolds Number***	***Development Length (m)***	***Column Length (m)***
1	25	18.7	337.1	0.38	0.8
2	34	27.7	261.9	0.43	0.68
3	49	42.7	190.9	0.49	0.5
4	70	63.7	138.4	0.53	0.62
5	105	98.7	94.9	0.56	0.52
6	143	136.7	70.8	0.58	0.52
7	197	190.7	52.0	0.59	0.52

Since the columns in the Environment Canada device contain a tube extending down the center, the column is referred to as an annulus. The laminar flow profile for an annulus can be derived using Equations 3.5 and 3.6. In Equation 3.5 the parameter $\left(\frac{\Delta p}{l} + \rho g\right)$ can be computed. This term is then used in Equation 3.6 to determine the upward velocity at any point in the cross section. Both equations are derived from Navier-Stokes equations, which are presented in Appendix A. Both the laminar and uniform flow profiles for the 105 mm column is displayed in Figure 3.4.

$$\left(\frac{\Delta p}{l} + \rho g\right) = \frac{Q * \frac{8\mu}{\pi}}{\left(r_{column}{}^{4} - r_{tube} - \frac{(r_{column}{}^{2} - r_{tube}{}^{2})^{2}}{\ln\left(r_{column}/r_{tube}\right)}\right)} \qquad \text{Equation 3.5}$$

where:

μ = dynamic viscosity

$$v_z = \left(\frac{1}{4\mu}\right)\left(\frac{\Delta p}{l} + \rho g\right)\left[r^{2} - r_{column}{}^{2} + \frac{r_{tube}{}^{2} - r_{column}{}^{2}}{\ln\left(r_{column}/r_{tube}\right)}\ln\left(\frac{r}{r_{column}}\right)\right] \qquad \text{Equation 3.6}$$

where:

v_z = upward velocity at radius, r

r = distance from center

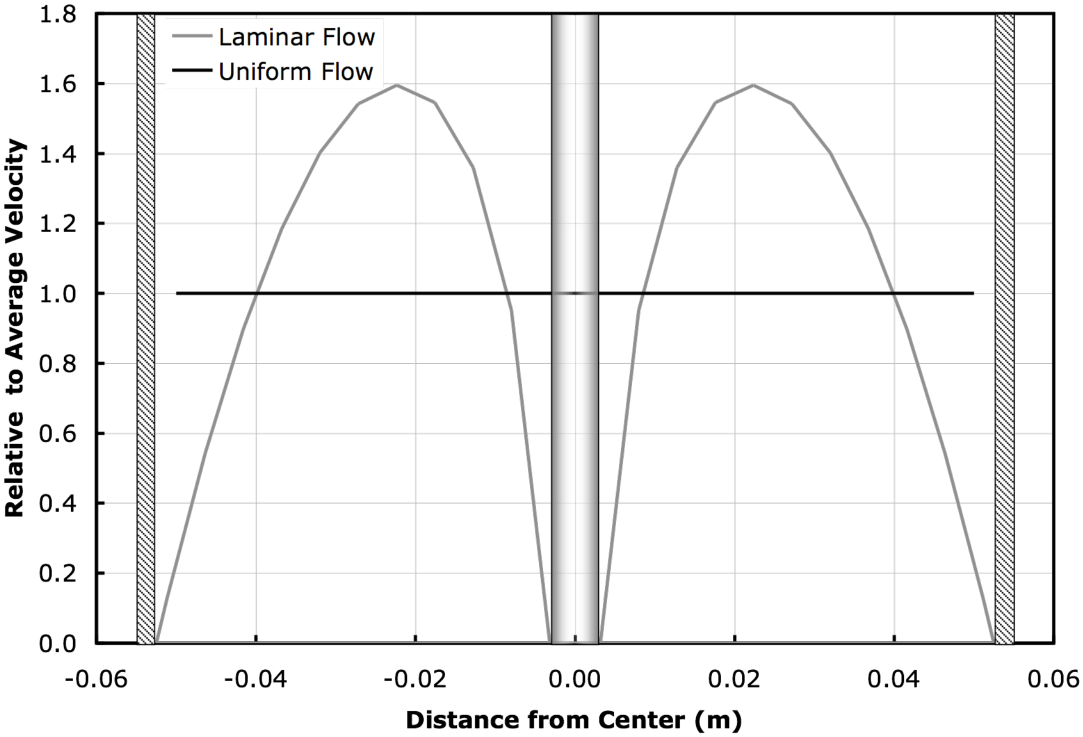


Figure 3.4. Laminar and uniform flow profiles for 105 mm column

3.3.4.3. Sediment traveling through columns

Each particle pumped into the system has a settling velocity that depends on size, shape, texture, and density. The Ferguson and Church equation presented in Chapter 2 can be used to compute the settling velocity for the various parameters. The settling velocity of the particle can then be compared to the upward velocities found in the columns of the Environment Canada device.

The amount of time required to flush a particle through a column can be calculated knowing the upward column velocity, particle settling velocity, and column length. First, the differential upward velocity of the particle can be determined by subtracting the upward velocity in the column by the settling velocity of the particle as shown in Equation 3.7. If the differential velocity is less than zero, the particle will be retained in the column. Otherwise, the amount of time for a particle to be flushed through a particular column can be determined using Equation 3.8. Finally, Equation 3.9 can be used to calculate the total amount of time to run the device.

$$\Delta v = v_{upward} - v_{settle}$$ Equation 3.7

where:

Δv = differential velocity
v_{upward} = upward velocity at a point in the column
v_{settle} = particle settling velocity

$$t_{flush} = \frac{l_{column}}{\Delta v}$$ Equation 3.8

where:

t_{flush} = time to flush particle through column
l_{column} = length of the column

$$t_{total} = \frac{V_{sediment} + V_{clean}}{Q}$$ Equation 3.9

where:

t_{total} = total operation time for device
$V_{sediment}$ = volume of water/particle suspension pumped
V_{clean} = volume of clean water pumped
Q = system flow rate

3.3.4.4. Model development in Microsoft Excel

A program incorporating uniform and laminar flow theories was developed using Visual Basic for Applications in Microsoft Excel. The model was utilized to determine the theoretical particle size distributions and compare them to the actual particle size distributions retained in each column. In the model many assumptions were made. First, a particle is assumed to exit a column if the amount of time it takes a particle to be flushed through the column (t_{flush}) is less than the total time since it arrived at the bottom of the column. Second, particles were assumed to be uniformly mixed in the influent. Third, the particles were assumed to be uniformly distributed across the cross-section of each column they entered. Finally, the time for a particle of a particular size to reach the bottom of the next column was assumed to be the length of the previous column divided by the average velocity in that column.

3.3.5. Environment Canada Device Results

Four tests to determine both mass and particle size distribution were performed on the Environment Canada portable elutriation device. An additional two tests were performed only measuring the mass retained in each column. The following sections contain the results from each of those four tests.

3.3.5.1. Results measuring mass retained in columns

A summary of the six experiments measuring the mass retained in each column is provided in Table 3.3. In Figures 3.5 through 3.10, the actual mass retained in each column is compared to the influent distribution, the expected distribution assuming uniform flow conditions in the columns, and the expected distribution assuming laminar flow conditions in the columns. The figures indicate the Environment Canada Device provides inconsistent results. Theoretical distributions were calculated using the methods and equations described in the previous section. Data was not collected for Run 3 because the device encountered an error in the middle of testing.

Table 3.3. Summary of results from six Environment Canada device runs

Run #	**Date**	**V_{sed} (L)**	**V_{clean} (L)**	**Q (L/min)**	**m_{in} (g)**	**m_{out} (g)**	**Δmass (%)**
1	1/25/09	20	20	0.43	8.00	7.65	-4.4
2	2/5/09	20	20	0.45	7.50	6.03	-19.6
4	2/26/09	20	20	0.44	7.50	7.28	-2.9
5	3/5/09	20	40	0.43	7.50	7.23	-3.6
6	7/21/09	20	20	0.45	10.00	9.55	-4.5
7	8/2/09	20	20	0.38	8.00	8.17	2.1

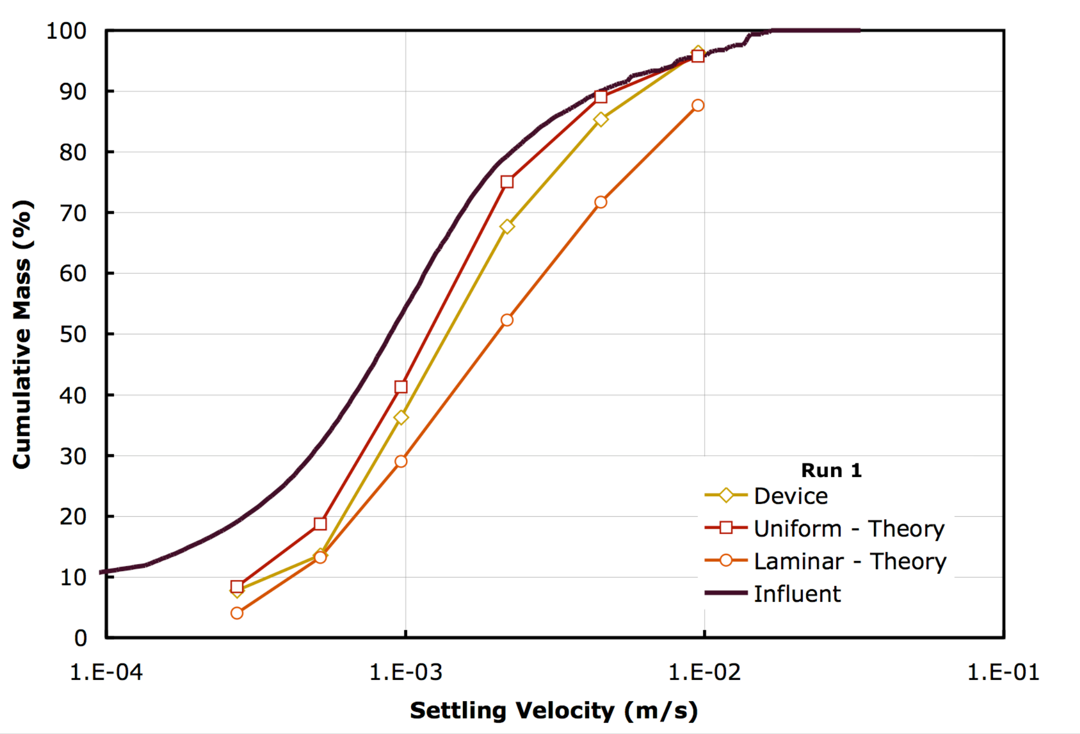


Figure 3.5. Cumulative distribution for Environment Canada Run 1.

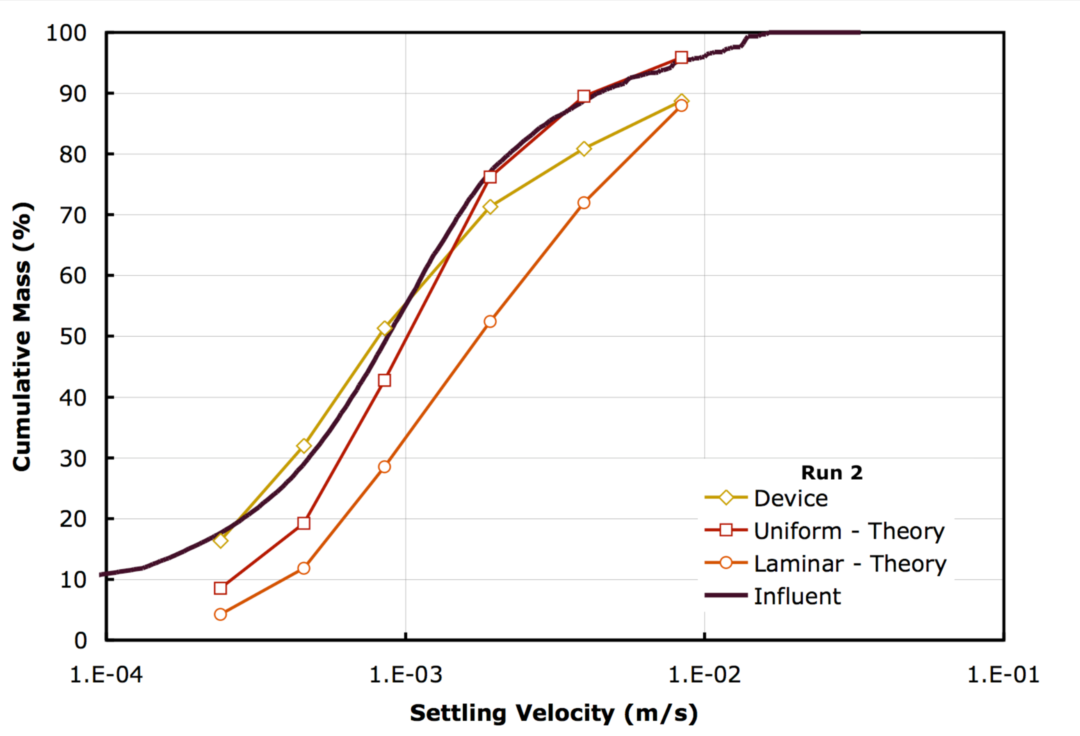


Figure 3.6. Cumulative distribution from Environment Canada Run 2.

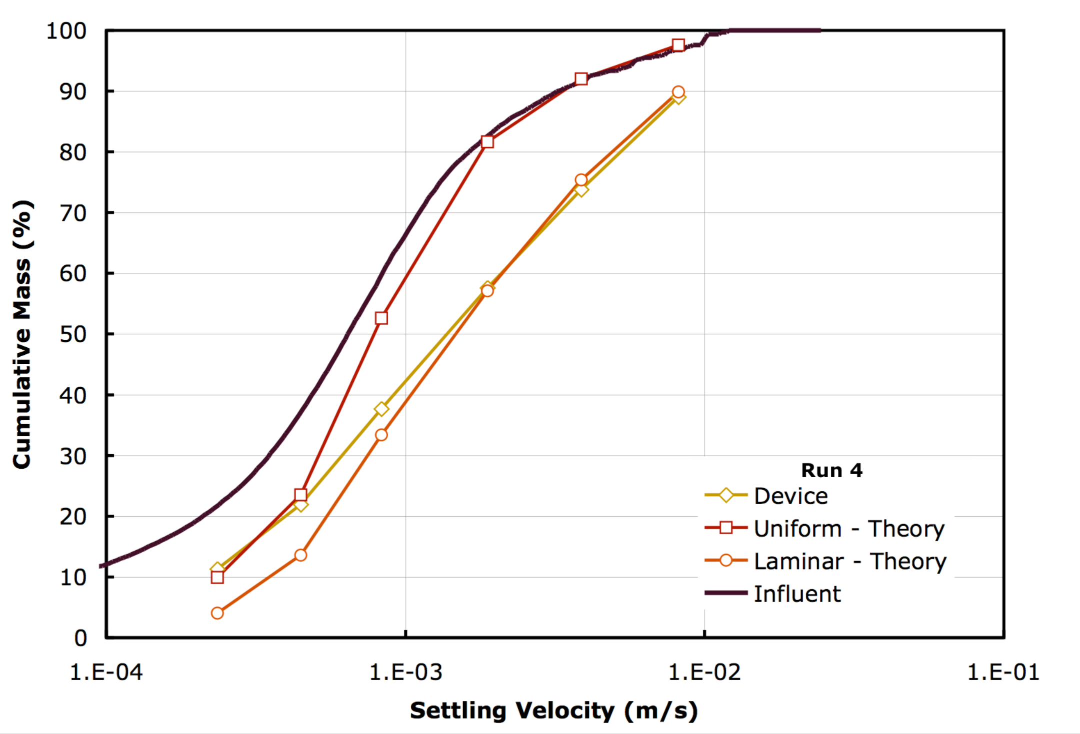


Figure 3.7. Cumulative distribution for Environment Canada Run 4.

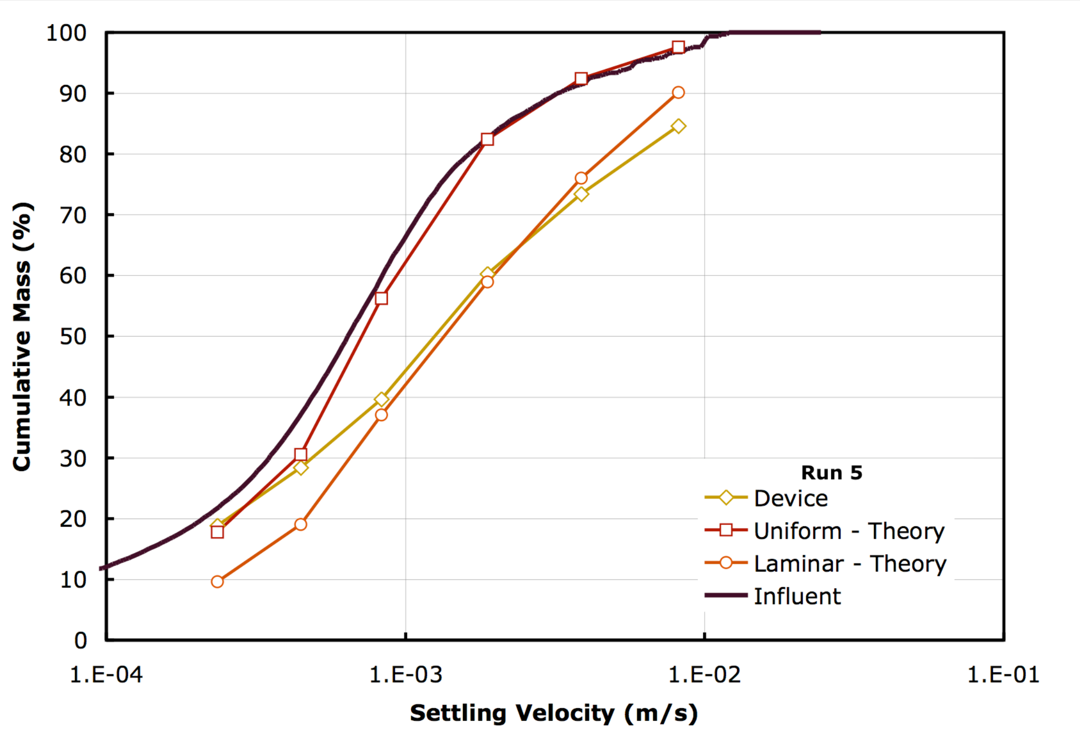


Figure 3.8. Cumulative distribution from Environment Canada Run 5.

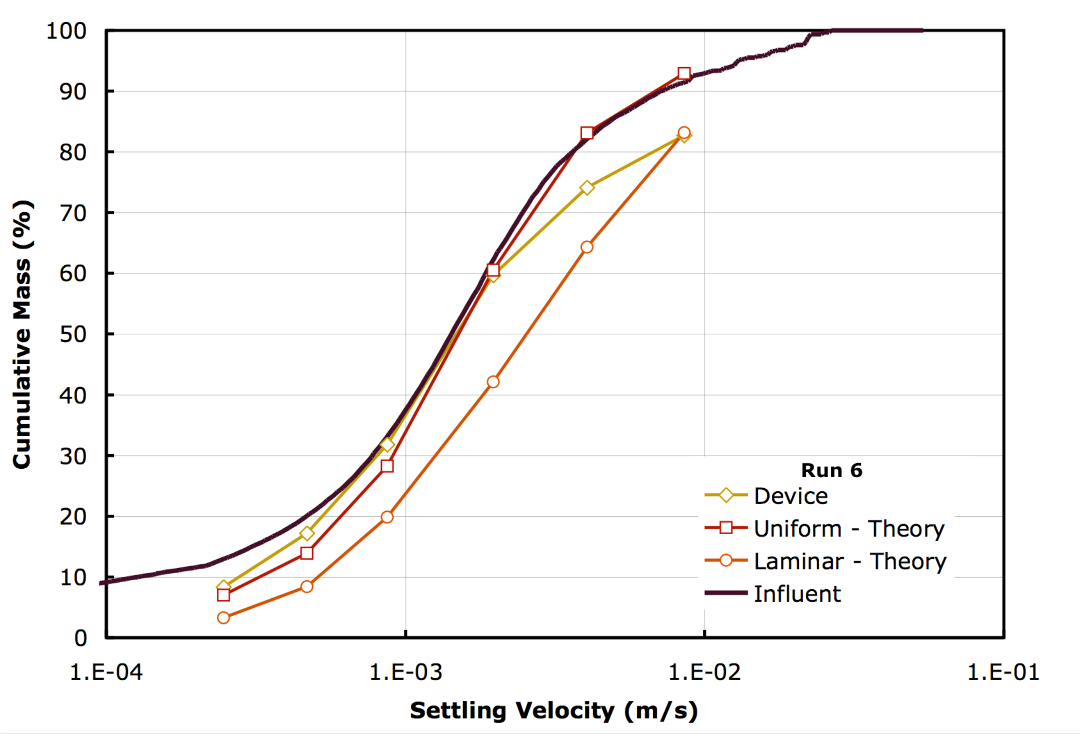


Figure 3.9. Cumulative distribution for Environment Canada Run 6.

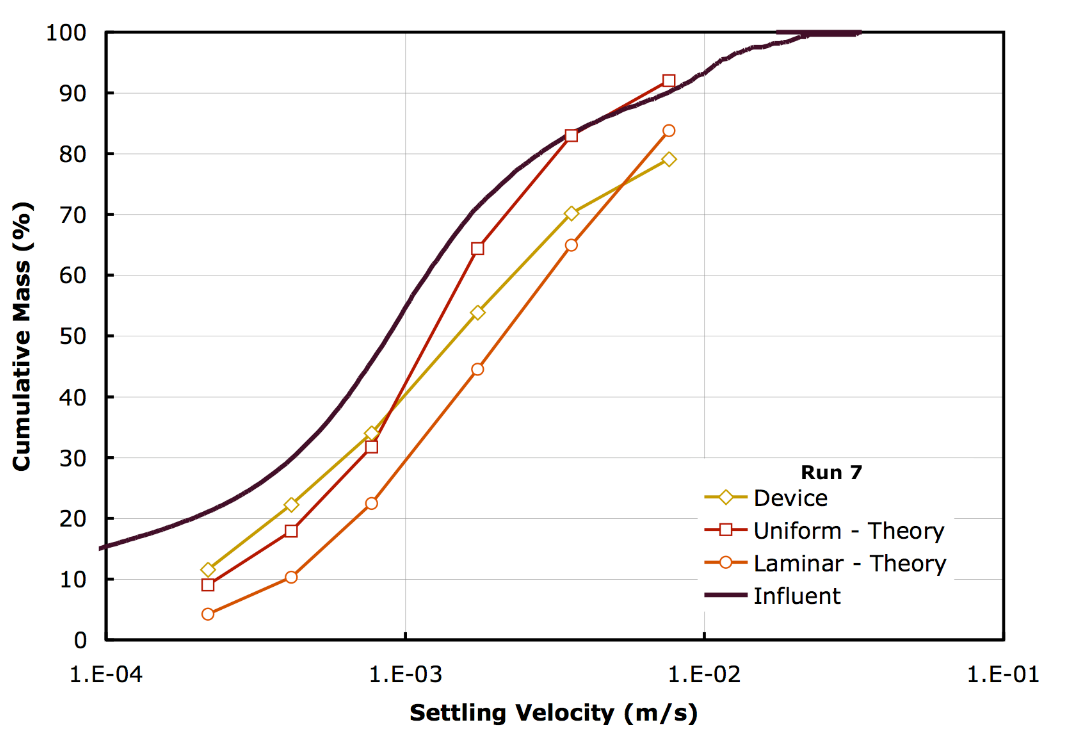


Figure 3.10. Cumulative distribution for Environment Canada Run 7.

3.3.5.2. Experiments measuring particle size distribution

Table 3.4 shows the d_{50} for each of the columns from the four tests measuring particle size distribution. The theoretical results in the table are calculated assuming a uniform flow profile.

The size distributions of particles retained in each column for runs 1, 2, 6, and 7 were measured are provided in Appendix B. The figures include both the measured particle size distribution and the particle size distribution expected in the respective column assuming a uniform flow profile in each column. Seven graphs for each experimental run are provided.

Table 3.4. d50 and percent difference for Environment Canada device

	34 mm column d_{50} (μm)			49 mm column d_{50} (μm)			70 mm column d_{50} (μm)		
Run	Actual	Theory	**%Error**	Actual	Theory	**%Error**	Actual	Theory	**%Error**
1	127	151	**16**	97	98	**1**	62	65	**4**
2	51	149	**66**	103	99	**4**	65	66	**1**
6	81	130	**38**	77	79	**3**	54	52	**6**
7	58	108	**46**	57	76	**25**	48	48	**1**

	105 mm column d_{50} (μm)			143 mm column d_{50} (μm)			197 mm column d_{50} (μm)		
Run	Actual	Theory	**%Error**	Actual	Theory	**%Error**	Actual	Theory	**%Error**
1	43	43	**0**	30	28	**5**	11	17	**36**
2	44	43	**3**	30	29	**6**	13	17	**21**
6	38	35	**8**	26	23	**13**	11	12	**8**
7	31	33	**7**	18	21	**17**	10	11	**6**

	Effluent d_{50} (μm)		
Run	Actual	Theory	**%Error**
1	6	6	**5**
2	8	6	**29**
6	12	5	**122**
7	6	6	**10**

3.3.6. Discussion of Environment Canada Device Results

The results for both mass and particle size distribution are displayed in the previous section. The distributions measured from the elutriation device fall between the theoretical distributions assuming a laminar flow profile and a uniform flow profile. In every experimental run, however, more mass than expected was retained in the 34 mm column. The size distribution of particles in the 34 mm column indicates the column contained many more fine particles than expected if a uniform velocity profile is assumed. This result could arise for a few reasons. First, the flow in the first column could truly be non-uniform. If the flow in the column is laminar, particles close to the column wall that would otherwise be flushed through the columns cannot exit the column because the upward velocity is lower near the wall. Second, the momentum of particles exiting the downward tube could carry the particles to the bottom of the column. The particles may get trapped at the bottom, would never enter the upward velocity profile, and would not exit the column

The median diameters of particles in the 70 mm, 105 mm, and 143 mm columns closely match the median diameters expected if a uniform flow profile is assumed. The median diameter and size distribution for the 34 mm, 49 mm, and 197 mm columns, however, do not match the distribution assuming a uniform flow profile. It is unclear why the size distributions for the middle three columns seem to match the theory, while the size distributions of particles retained in the other columns do not match the theoretical distributions. Additionally, Figures 3.5 to 3.10 indicate the Environment Canada Device provides inconsistent experimental results.

3.3.7. Difficulties with Operation of Environment Canada Device

Two main complications arose with the operation of the Environment Canada elutriation device. The main operational difficulty was the result of the device requiring constant suction to operate. As indicated previously, the 25 mm diameter column was not used in the experiments. Since the column only had room for the tube extending down the column, the outlet of the column was formed from glass. An airtight seal between the latex tubing and the glass outlet could not be established. Since a proper seal was required for the operation of the device, the 25 mm column was bypassed.

Establishing airtight seals throughout the device was also a problem with the operation. Air could enter the device at the connection between the glass columns and the rubber stoppers and also at the connections between the latex tubing and the hard plastic tubing inserted through the rubber stoppers. If air leaked into the device at any point in the system, air pockets would collect at the top of the columns. If the air pocket dropped below the outlet tube, water stopped being pulled through the system. Air leaks developed at one of the connections in numerous runs, and the runs had to be abandoned as a result.

The amount of time required to operate the device was also an operational concern. Setting up the columns, establishing airtight seals, and pumping 40 liters of water through the device took over three hours. Since the device was susceptible to air leaks at the many connections, someone had to constantly attend the device so leaks could be stopped before disrupting the operation of the system. Collecting the samples from the various columns took another hour. Finally, filtering and drying the samples collected from the columns took two hours. In total operating the Environment Canada device to obtain a single settling velocity distribution took approximately six hours.

4. Updates to Elutriation Device

To overcome the operational difficulties associated with the prior design of the elutriation device and make a more robust device, modifications to the traditional design were made. The modifications included changes to the pump, changes to the columns, and changes to the inlet and outlet of the device.

4.1. Modifications Made to Environment Canada Device Design

Figure 4.1 shows the evolution from the Environment Canada columns to the final column design. Many design iterations were used to develop the final columns, but only the design of the final columns are discussed in the following sections. Changes made to the Enviroment Canada device design are summarized in Table 4.1 and are explained in the following sections. Despite the modifications, the concepts for the operation of the device are the same as the concepts used in previous designs.

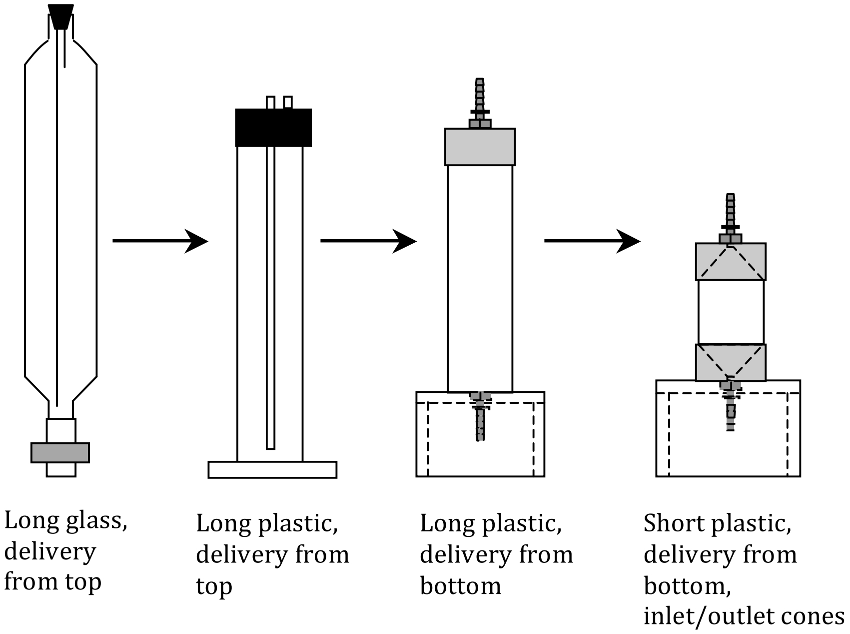


Figure 4.1. Evolution from Environment Canada column to final column design.

Table 4.1. Summary of modifications made to Environment Canada device

Modification	**Justification**
Pump	
Move pump downstream	Easier to use
Variable speed pump	Broader applications
Column	
Replace glass with plastic	Cheaper, lighter, less fragile
Shorten columns	Shorter run times
Provide funnel at bottom	Avoid eddies
Fewer columns	Smaller sample required
Inlet/Outlet	
Deliver sample at column bottom	Ensure suspension of particles
Install screen at column bottom	Reduce effect of jet
Direct outlet flow to one point	Increase accuracy

4.1.1. Pump Modifications

Modifications were made to the pump to improve the functionality and provide flexibility in the applications of the device. First, the peristaltic pump was moved from the downstream end of the device to the upstream end of the device. When the pump was located downstream, the suspension was pulled through the device using suction, and the system required airtight seals throughout the system. As discussed in Chapter 3, the seals are difficult to establish and maintain, and the device stops functioning if one of the seals failed. Pushing water through the system instead of relying on suction eliminated the operational issues. Although operation of the device was improved, placing the pump upstream can potentially affect the sample by breaking up flocs of particles. The consequence was a concern for researchers measuring the settling velocity of river sediment or particles in combined sewer overflows. However, it should not be a significant issue for urban runoff because most of the particles are more often granular.

When a variable speed peristaltic pump is used, operation of the device becomes more flexible. Instead of having a fixed flow rate, the pump can be adjusted to increase or decrease the flow rate. If the flow rate through the system is increased, the particles retained in each of the columns will be coarser because upward velocity in the columns increases. Conversely, a lower flow rate leads to finer particles being retained in each of the columns. Flexibility associated with a variable flow pump allows the device to be used for a wide range of settling velocities and applications.

4.1.2. Column Modifications

Modifications were also made to the columns in the elutriation device. The columns of the modified elutriation device were constructed from clear plastic tubes rather than custom blown glass. Plastic was selected for numerous reasons. First, plastic columns are much cheaper than the custom blown glass columns. Second, a series of plastic columns is much lighter than a series of glass columns, which means the device is more portable and easier to use. Finally, plastic is more durable than glass. If the elutriation device were used in the field, concerns about fragile glass if one of the columns is dropped are eliminated. The drawback to plastic columns is the possibility of small, organic particles attaching to the walls. This concern is not believed to be a significant problem for stormwater runoff, but it should be noted in field applications and would make measurements on CSOs, like the Environment Canada device's use, difficult.

The columns in the system were also shortened when compared to the glass columns used in previous studies. The shortened columns decrease the amount of time a sample has to be run through the device. As described in Chapter 3, the relative upward velocity of particles depends on the upward velocity of the fluid and the settling velocity of the particle. For particles with settling velocities slightly less than the upward fluid velocity, the relative upward velocity is small. The particles must travel to the top of the columns so they can flow through the exit and be adequately separated into their respective settling velocity distributions. The time required for a particle to reach the top of the column is directly proportional to the column length so decreasing the length of the column decreases the amount of time required for a particle to be flushed through the column. The decrease in time ultimately translates to a smaller volume of sample that needs to be flushed through the system.

The bases of the columns were modified to improve operation of the device. Rather than having custom blown glass columns, cone-shaped inserts with size angles at 45-degrees were installed at the top and bottom of the columns. At the bottom of the column, the cone acts as a diffuser and helps reduce eddies that could form along the sharp edges of the cylindrical plastic columns. At the top of the column, the cone helps direct the sample to the outlet. Either a simple plastic funnel can be used for the cone, or a block of aluminum can be machined to achieve the desired shape and slope.

The final modification to the columns in the device involved a decrease the number of columns used. The Environment Canada device used up to eight columns to determine the settling velocity distribution. The detailed settling velocity distribution obtained from the eight columns is not necessary in the design of stormwater treatment practices because the elutriation device can be calibrated so the first column retains all particles with a settling velocity greater than the overflow velocity of the settling operation. The main advantage of decreasing the number of columns is a decrease in the volume of stormwater sample required.

4.1.3. Inlet and Outlet Modifications

The inlet and the outlet of the columns were also updated in the modified elutriation device. When a long tube extending to the bottom of the column delivers the sample, the particles enter with a downward momentum and may get caught in the bottom. Instead of this setup, the device was modified to deliver the sample upward from the bottom of the column. When delivered from the bottom, the particles enter the column system with an upward momentum so every particle will start in suspension.

Delivering the sample to the columns directly from the bottom of the column causes the fluid stream to enter the column as a jet, which is not desirable for the operation of the elutriation device. An effective way to promote a uniform velocity profile is to create head loss in the column cross-section. Many combinations of wire-mesh screens were added towards the bottom of the column to generate head loss and produce a more uniform velocity profile. Ultimately, four of the 60x60 mesh screens with 31 percent open area were installed at the bottom of the column. The modified column operating without screens is shown in Figure 4.2. The combination of screens promoted an even distribution of flow as shown in Figure 4.3. By evenly distributing the flow, the wire-mesh screens also allowed the column to be shorter.

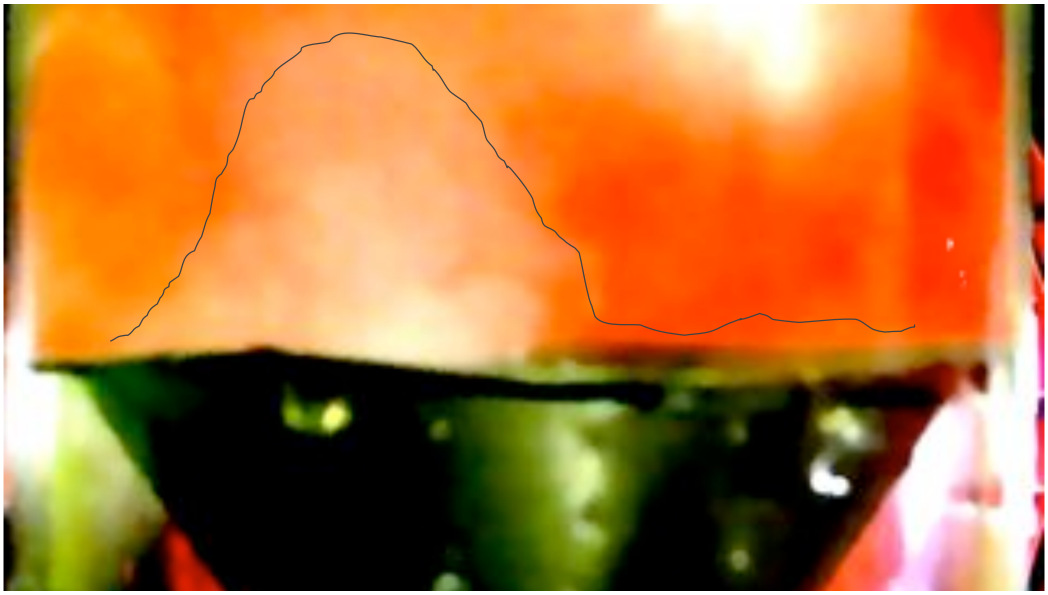


Figure 4.2. Particles unevenly distributed across the column without screens.

Figure 4.3. Particles evenly distributed across column with four screens in the diffuser.

4.2. Updated Single Column

A single column was tested to evaluate the effectiveness of the modifications described in the previous section. The single column was originally constructed using a piece of clear 3.75 inch (95 mm) PVC pipe, plastic funnels, a rubber cap to seal the top of the of the device, and plastic tubing for the inlet and outlet of the device. The prototype single column was used to study the effect of many modifications and could be observed quickly and easily. A final design composed of aluminum caps, plastic columns, and screens was eventually developed from this prototype.

4.2.1 Experimental Methods

Like the Environment Canada device, the single column device required operation, sample collection, and sample analysis. The main difference between the operation of the Environment Canada Device and the single column device, however, was the use of only one column rather than six columns.

4.2.1.1. Operation of single column device

Methods for operating the single column are similar to the methods used in operating the Environment Canada device. To operate the single column device, ten liters of tap water was collected in a plastic 20-liter bucket. Three grams of ground silica of a known size distribution and density was measured. For most experiments, the ground silica mixture was composed of 90 percent sieved between 44 and 88 micrometers, 5 percent sieved between 88 and 125 micrometers, and 5 percent sieved percent between 125 and 240 micrometers. The silica in the study was dry sieved, but many particles smaller than 44 micrometers remained in the mixture.

The ground silica mixture was added to the ten liters of tap water and mixed well with either an electric mixer or a hand-powered mixer. Once the ground silica was suspended in the ten liters of water, the peristaltic pump connected to the single column was turned on. While the pump operated, the influent mixture continued to be well mixed to suspend the particles. When the entire volume of influent mixture was almost pumped out of the bucket, another five liters of clean tap water was added to the bucket and pumped through the device. All effluent during the operation was collected in another clean 20-liter bucket.

At intervals throughout the operation of the single column device, the flow rate was measured. Flow rate was measured by calculating the amount of time required to pump a known volume, typically 500 or 1000 milliliters. Volume was divided by time to determine a flow rate. Once the sediment mixture and clean water were both pumped through the device, the pump was turned off so samples could be collected.

4.2.1.2. Sample collection

In order to determine the effectiveness of the device, the influent particle size distribution was determined. To determine the influent particle size distribution, three 30 milliliter grab samples of the tap water and sediment mixture were collected when the mixture was well mixed. The grab samples were analyzed using the Multisizer 3 Coulter Counter described in Chapter 3.

Once the single column operation was completed, additional samples were collected. First, the sediment retained in the column was collected by operating the pump in reverse. The water from the column was collected in a clean 2000 milliliter beaker, and the sides of the column were washed using a spray bottle filled with deionized water. Any screens used in the column were also well washed using the spray bottle. Finally, the bottom funnel was washed with the spray bottle, and all water was collected.

The sediment flushed through the device also had to be characterized. The effluent sample was well mixed by transferring the effluent water/sediment mixture between two buckets six times. Once the mixture was well mixed, three 30 milliliter grab samples are collected. Additionally, three 200 milliliter TSS samples were taken from the effluent. The TSS samples were collected using a standard 100 milliliter pipet with a wide tip. Between each sample collection the effluent mixture was mixed using the two bucket method.

4.2.1.3. Sample analysis

To determine the mass retained in the column and in the effluent, the respective samples were filtered through filters with nominal pore size of 0.45 microns. The first step was measuring and recording the mass of ceramic crucibles containing the filters. Once the filters' mass was determined, individual crucibles were connected to a beaker attached to a pump generating suction, and samples were passed through the crucibles. The container holding the water from the column was washed out to ensure all sediment was collected. For the effluent samples, each 200 mL sample was passed through its own individual filter.

Once the samples were passed through the filters, the crucibles were dried in an oven at 100°C for one hour. The crucibles were removed from the oven and allowed to cool for fifteen minutes. The mass of the crucible plus sediment was measured and recorded, and the total mass of the sediment was determined by subtracting the initial crucible mass from the final crucible mass. The mass of sediment collected from the column represented the total mass retained in the column. Calculations were made to determine the mass in the effluent. The mass of sediment from the three 200 milliliter samples was averaged and divided by 200 milliliters to determine the concentration of particles in the effluent. The concentration of particles was multiplied by the total volume of the effluent (15-liters) to determine the total mass retained in the effluent.

The particle size distribution of the particles in the effluent and column was also measured to determine the effectiveness of the single column. To determine the particle size distribution, the 30 milliliter grab samples collected from the effluent were used and the total mass of particles retained on the dried filter was collected. The particles in each of the samples were passed through a Beckman-Coulter Multisizer 3 Coulter Counter to determine the respective particle size distributions.

4.2.2. Theoretical Performance

The theoretical performance of the single column device is similar to the theoretical distributions for the Environment Canada elutriation device. Since the flow is introduced directly from the bottom rather than from a tube extending from the top to the bottom, the flow through the single column is strictly flow through a cylinder rather than flow through an annulus.

4.2.2.1. Uniform flow profile

The uniform flow profile assumption is the simplest assumption that can be made for the single column device. Since the diameter of the column is known, the cross-sectional area can be calculated using Equation 4.1. The average upward velocity in the column can be calculated by dividing the flow rate by cross-sectional area as shown in Equation 4.2.

$$A = \frac{\pi\left(d_{column}^{\ 2}\right)}{4}$$ Equation 4.1

where:

A = cross-sectional area
d_{column} = inner diameter of elutriation column

$$v_{upward} = \frac{Q}{A}$$ Equation 4.2

where:

v_{upward} = upward velocity in column
Q = flow rate through column

4.2.2.2. Laminar flow profile

Laminar flow conditions occur for small Reynolds numbers. During operation of the single column, the pump was operated between a range of 0.75 L/min and 1.25 L/min. Since the initial prototype column is 95.25 mm in diameter, the Reynolds number in the column ranged between 167 and 278. With such low Reynolds numbers, the flow is conducive to laminar flow conditions. However, as calculated from Equation 3.4, the development length to achieve truly laminar flow was 1.0 meter for the lowest flow rate and 1.7 meters for the highest flow rate. Since the single column was only 0.2 meters in length, the laminar flow profile may not have enough time to fully develop.

The laminar flow profile for a cylinder is different than the flow through an annulus as described in Chapter 3. It can be calculated using Equations 4.3 and 4.4, which are calculated by solving the Navier-Stokes equations assuming fully developed flow. Although fully developed flow is not achieved in the columns, it can be assumed that this velocity profile is approached as the flow moves downstream. A derivation of the equations is provided in Appendix C. When Equation 4.3 is rearranged, the parameter $\left(\frac{\Delta p}{l} + \rho g\right)$ is computed using known values for the flow rate and the column radius. This term is then used with other assumptions to develop Equation 4.4, which calculates the upward velocity at any point in the cross section of the flow. Both the laminar and uniform flow profiles for the column with a flow rate of 1.0 L/min are displayed in Figure 4.4.

$$Q = \frac{\pi R^4}{8\mu}\left(\frac{\Delta p}{l} + \rho g\right) \qquad \text{Equation 4.3}$$

where:

R = column radius (m)

$$v_z = \frac{2Q}{\pi R^4}\left(R^2 - r^2\right) \qquad \text{Equation 4.4}$$

where:

r = distance of a point from the column center (m)

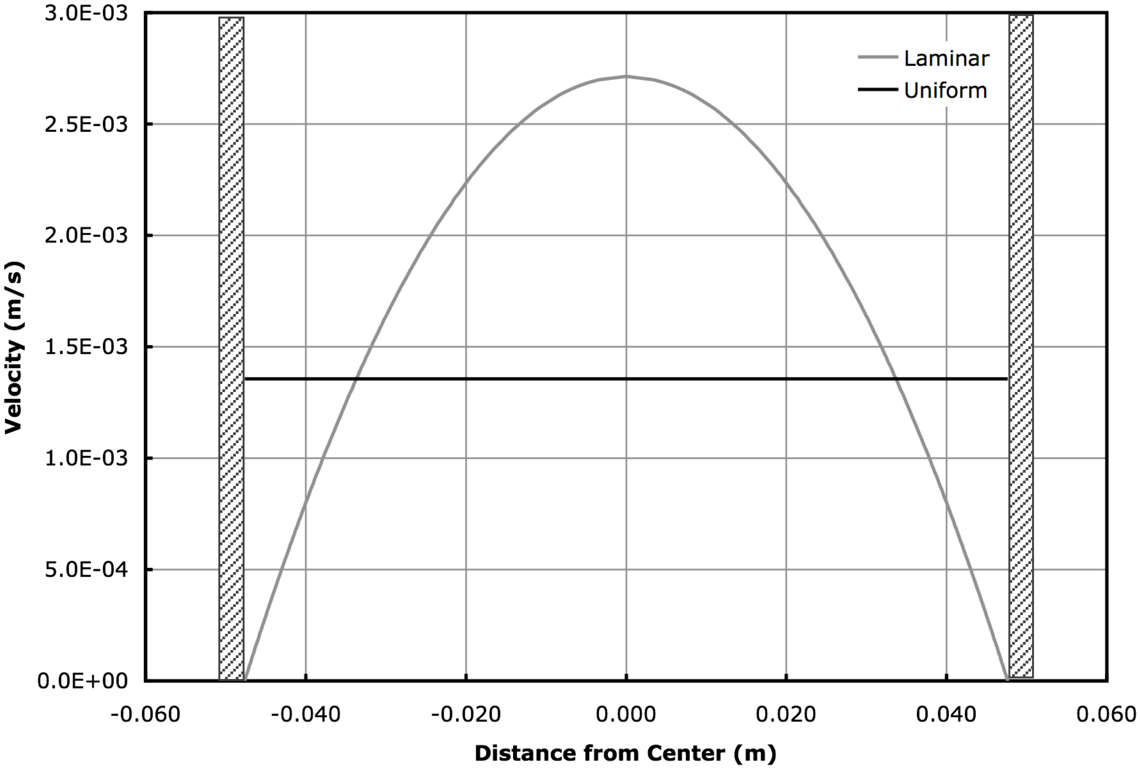


Figure 4.4. Laminar and uniform flow profiles for single column device.

4.2.2.3. Sediment passing through column

The mechanism of sediment passing through the single column is similar to that described for the Environment Canada device. If a particle has a settling velocity greater than the upward velocity in the column, it will be retained in the column. If the particle has a lower settling velocity than the upward velocity, the particle will eventually be flushed through the system. Calculating the time required to flush a particle through a column can be calculated using the same equations described in Chapter 3.

4.2.2.4. Model development in Microsoft Excel

A model for the single column device was also developed in Visual Basic for Applications in Microsoft Excel using both uniform flow and laminar flow theories. As with the model developed for the Environment Canada columns, particles were assumed to be uniformly mixed in the influent. Additionally, the particles were assumed to be uniformly distributed across the cross-section of each column they entered. The computer model was utilized to compare theoretical concepts with the actual results from the experiments of the single column. The program to determine the particle size distributions retained in the updated columns is provided in Appendix F. The program in Appendix F can accommodate calculations for up to three columns in series, which will be described in the next section.

4.2.3. Single Column Results

The particle size distributions of the particles retained in the column and the particle size distribution of particles in the effluent were compared to theoretical results for two different assumptions: uniform flow profile and laminar flow profile. The comparison for the particles retained in the column and effluent assuming a uniform flow profile is provided in Figure 4.5. The comparison for particles retained in the column and effluent assuming a laminar flow profile is presented in Figure 4.6. The results are presented for the final design of the updated single column device, which consisted of a smooth aluminum cone and four fine mesh screens at the bottom of the column.

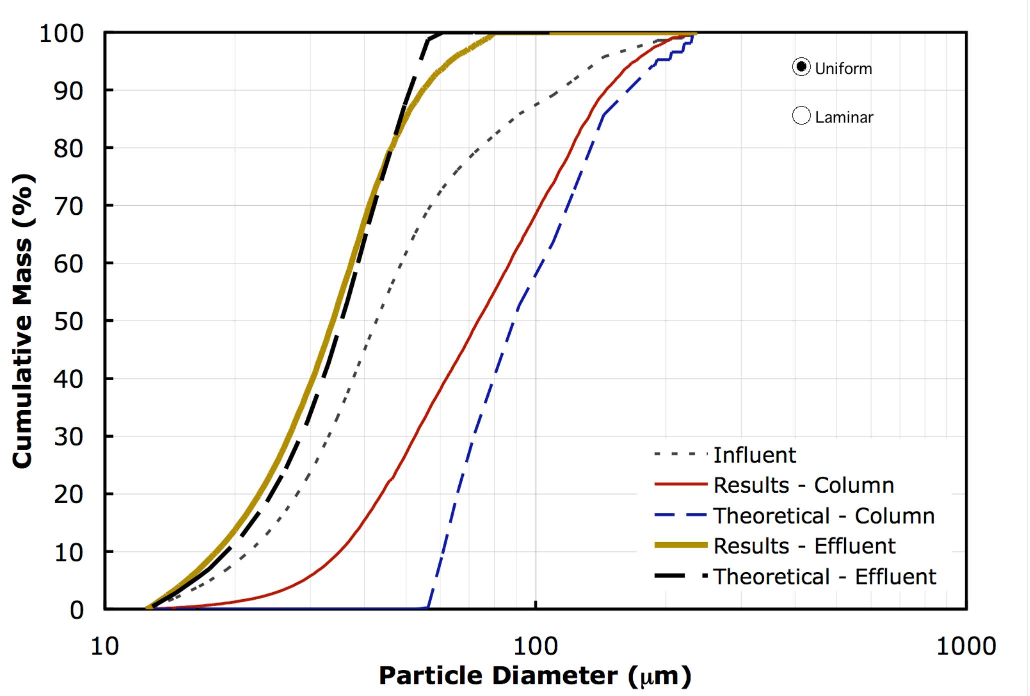


Figure 4.5. Particle size distribution for particles retained in updated column and effluent assuming uniform flow profile.

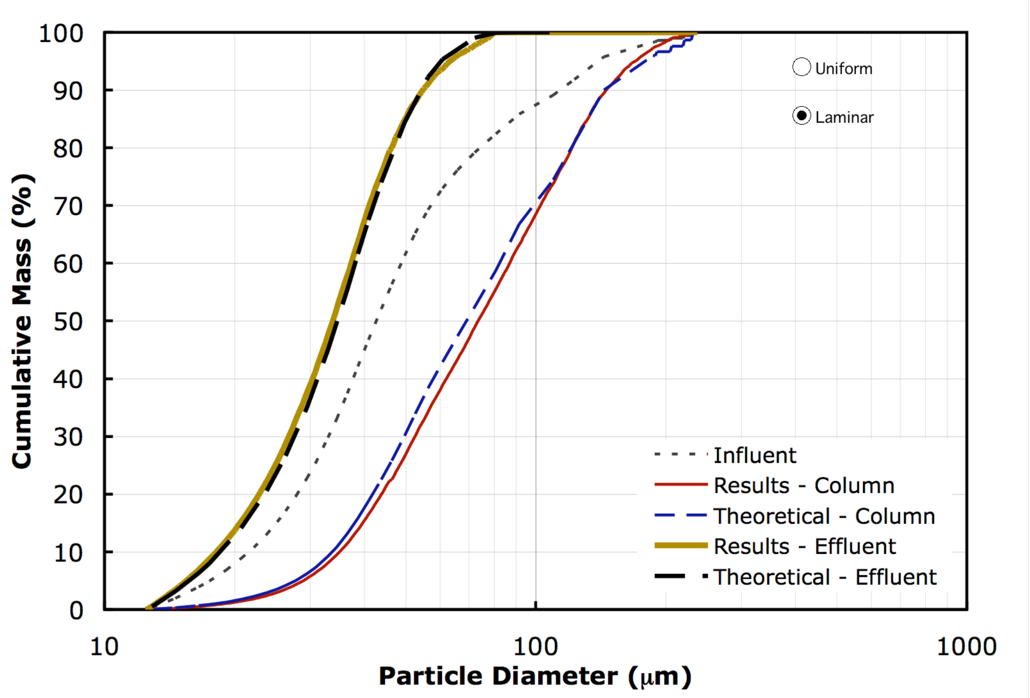


Figure 4.6. Particle size distribution for particles retained in updated column and effluent assuming laminar flow profile.

4.2.4. Discussion of Single Column Results

As displayed in Figures 4.5 and Figure 4.6, the particle size distributions of particles retained in the column and flushed to the effluent closely match the particle size distributions modeled assuming a laminar flow profile. The results are curious for a few reasons. First, the particles in the updated single column with four screens to diffuse the jet appeared to be evenly distributed across the column cross-section. Given the initial distribution, one might expect the column results to more closely match a uniform flow profile assumption. Second, the development length for the single column at the flow rates used in the experiments is approximately one meter. The actual single column, however, was only 0.2 meters in length. The laminar flow profile does not fully develop as the fluid passes through the 0.2 m length column. It may be that the combination of a developing velocity profile and the constriction into the cone at the top of the column resulted in a laminar-like distribution of residence time in the column. Nonetheless, assuming a laminar flow profile appears appropriate when estimating the actual results produced from the updated single column elutriation device.

4.3. Modified Elutriation Device with Multiple Columns

The modifications tested on the single column elutriation device were used to develop an elutriation device with three columns (hereafter referred to as the modified elutriation device). The three columns were 2.47 inches (63 mm), 3.9 inches (99 mm), and 6.0 inches (152 mm) in diameter. The base and top of the modified elutriation device were crafted from aluminum cylinders machined to have a cylinder with side angles of 45 degrees, and the columns were made from clear plastic piping with a length equal to the pipe diameter. Inlet and outlet hose fittings with an inside diameter of ¼ inch (6.3 mm) were installed at the centers of the base and top cap, and the columns were connected using ¼ inch (6.3mm) PVC plastic tubing. Additionally, four fine mesh screens were secured in the column base to evenly distribute flow across the device. Each of the columns rests on a 7.5 inch

(19.1 cm) square base that is 5 inches (12.7 cm) tall. A schematic of the 3.9 inch (99 mm) column of the modified elutriation device is shown in Figure 4.7. Detailed dimensions are provided in Appendix D.

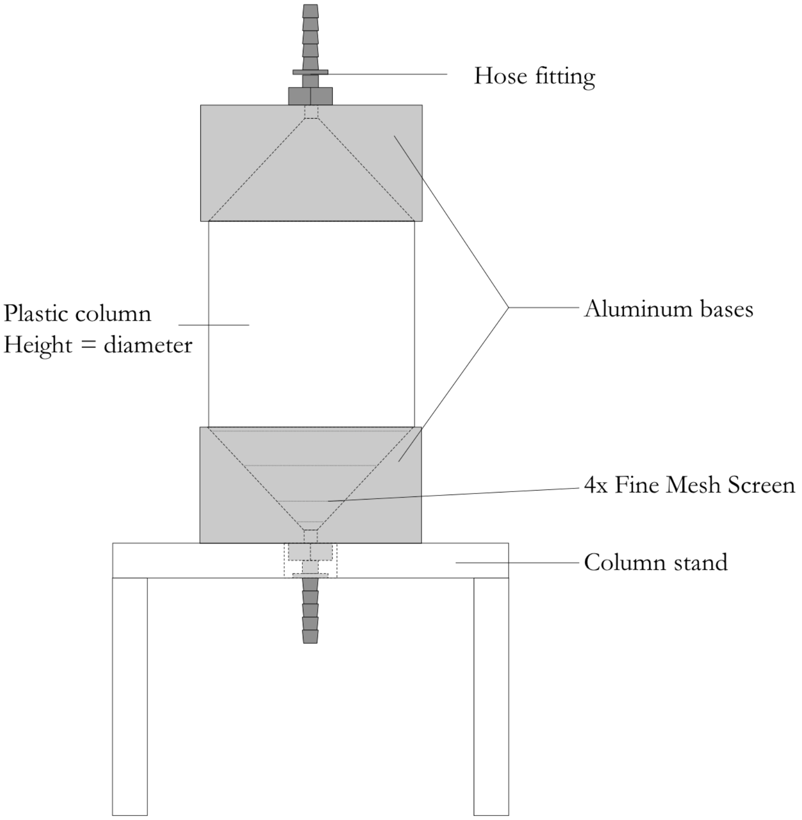


Figure 4.7. Schematic of 3.9 in. (99 mm) column from modified elutriations device.

4.3.1. Results for Individual Columns

The individual columns of the modified elutriation device were tested to verify the performance. Methods to test the columns were the same as the methods for the single column device, which is outlined in the previous section. Results from all three columns closely matched results expected if a laminar flow profile rather than a uniform flow profile is assumed. Column and effluent particle size distributions for uniform flow profile and laminar flow profile assumptions are respectively presented in Figures 4.8 and 4.9 for the 2.47-inch (63 mm) column, in Figures 4.10 and 4.11 for the 3.9-inch (99 mm) column, and in Figures 4.12 and 4.13 the 6-inch (152 mm) column.

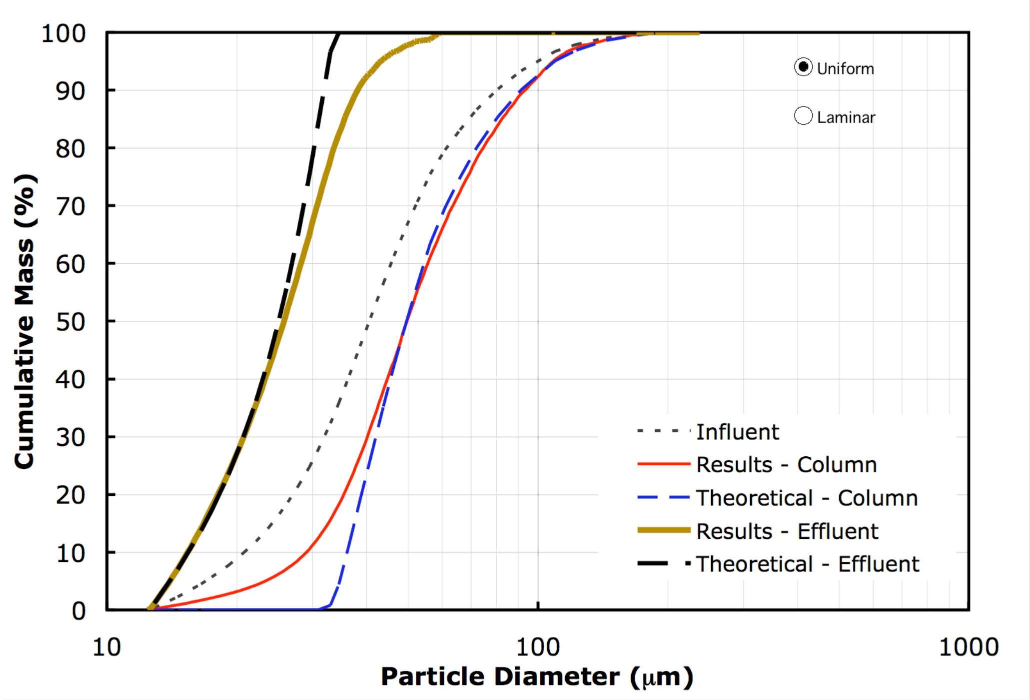


Figure 4.8. Particle size distribution for particles retained in column and effluent for 2.47 inch (63 mm) column assuming uniform flow profile.

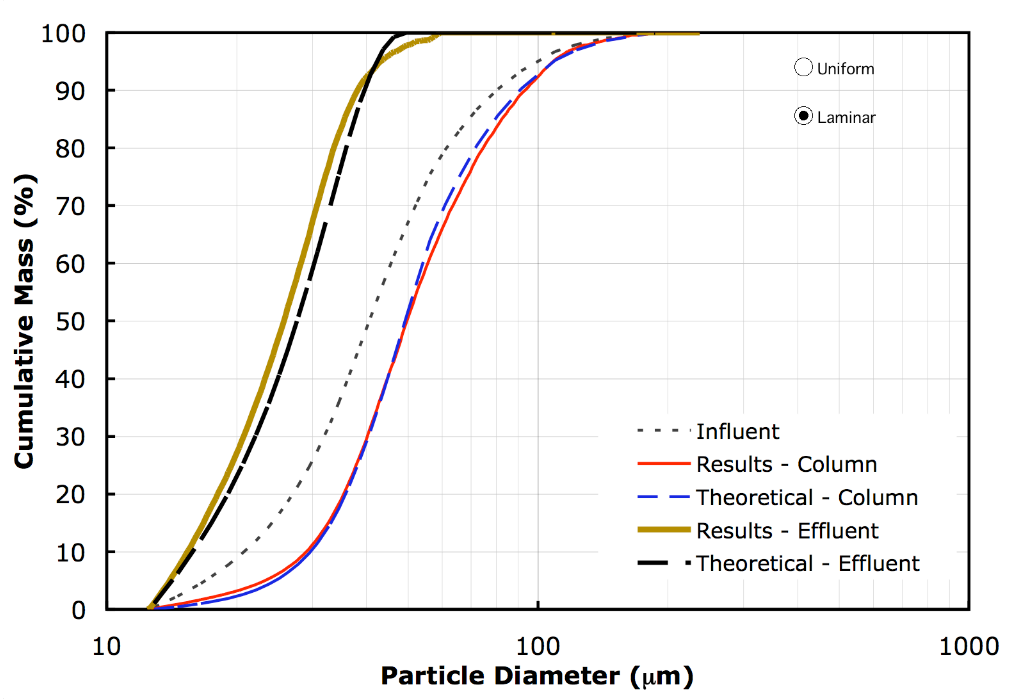


Figure 4.9. Particle size distribution for particles retained in column and effluent for 2.47 inch (63 mm) column assuming laminar flow profile.

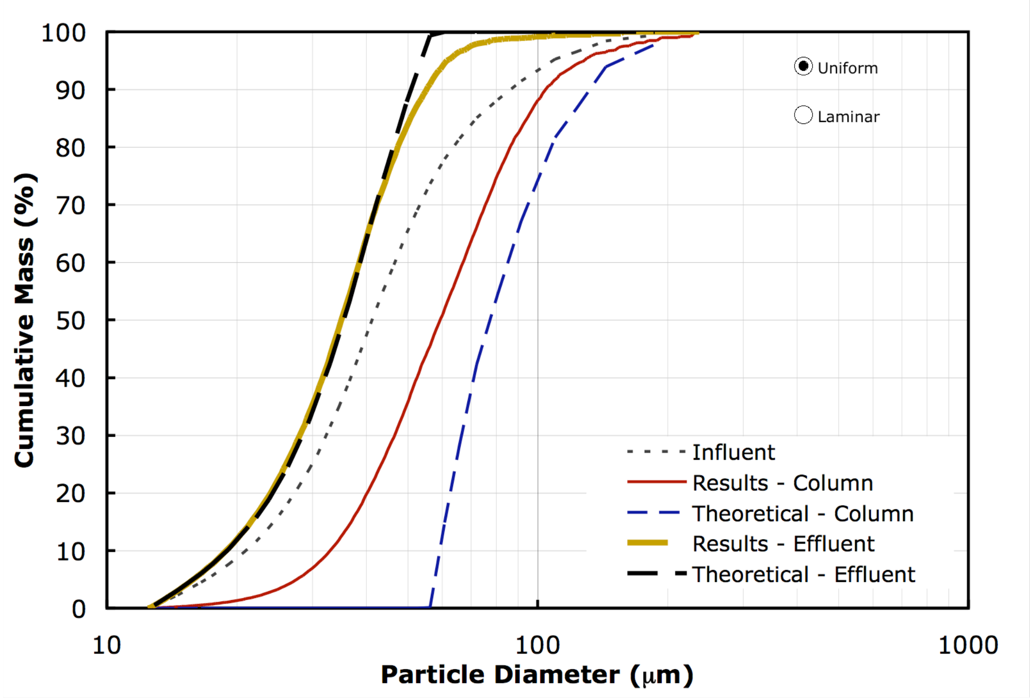


Figure 4.10. Particle size distribution for particles retained in column and effluent for 3.9 inch (99 mm) column assuming uniform flow profile.

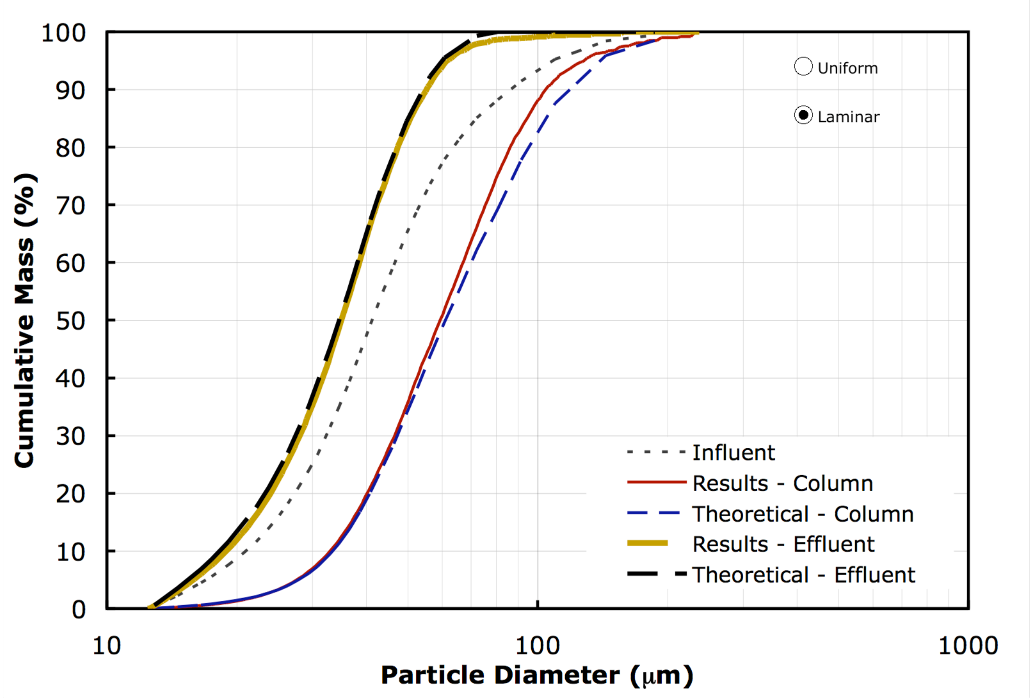


Figure 4.11. Particle size distribution for particles retained in column and effluent for 3.9 inch (99 mm) column assuming laminar flow profile.

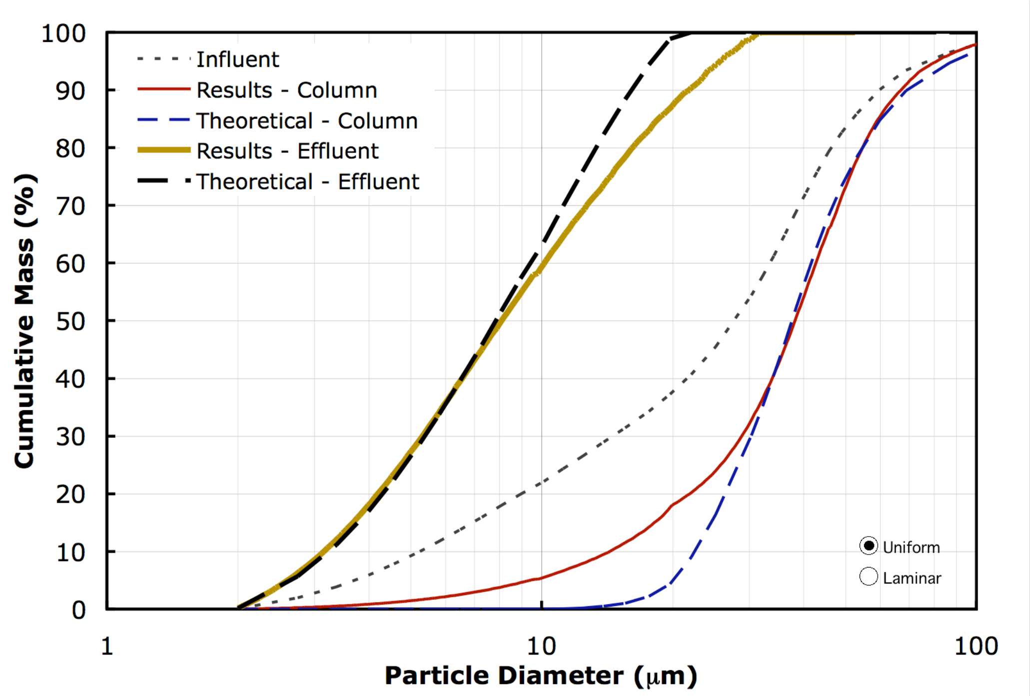


Figure 4.12. Particle size distribution for particles retained in column and effluent for 6 inch (152 mm) column assuming uniform flow profile.

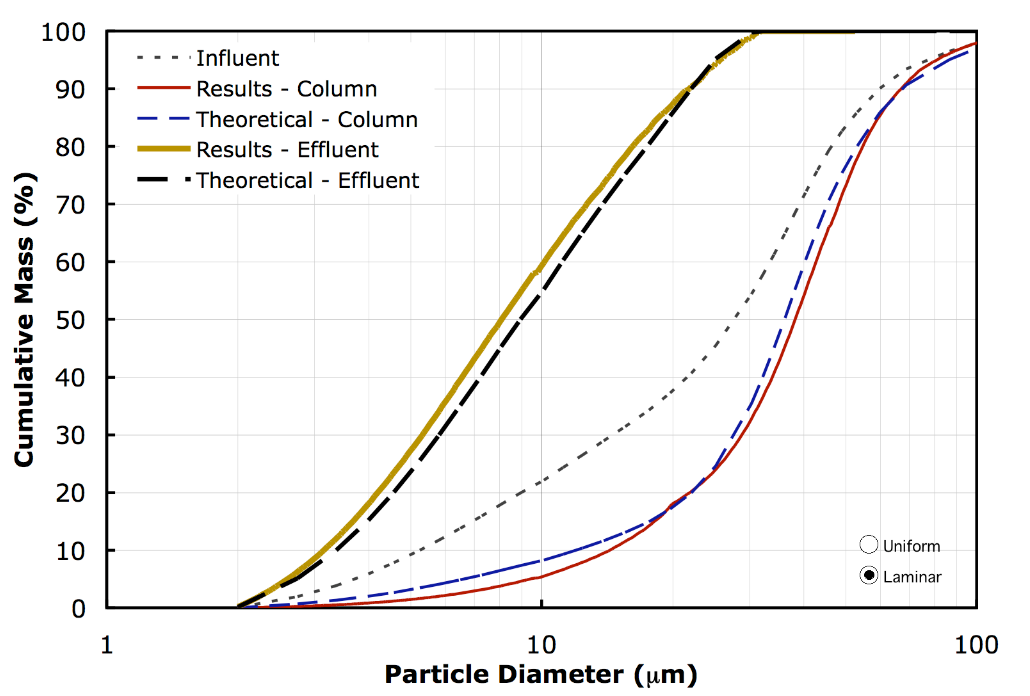


Figure 4.13. Particle size distribution for particles retained in column and effluent for 6-inch (152 mm) column assuming uniform flow profile.

4.3.2. Operation of Modified Elutriation Device

The modified elutriation device is composed of three columns similar to the column pictured in Figure 4.7. The operation of the device is similar to operation of the updated single column presented in the previous section. Instead of using one column, however, the device is operated with a combination of columns and a variety of flow rates. The two primary methods to operate the modified elutriation device are described below. A standard operating procedure for the device is provided in Appendix D.

1) Three columns, single flow rate: The three columns of the modified elutriation device are arranged in order from smallest diameter to largest diameter. With this particular setup the device is operated once at a single flow rate.
2) Three columns, two flow rates: To obtain a wider settling velocity distribution, the modified elutriation device is operated at two flow rates. In this setup the two smallest diameter columns are connected to the pump, and the device is operated at a higher flow rate (1.5-2.0 L/min). After the mass in each column is collected, the effluent is pumped through all three columns at a lower flow rate (0.25-0.50 L/min). The mass in these three columns is then collected, and a broader settling velocity distribution is calculated. Figure 4.14 shows a schematic of how this system operates.

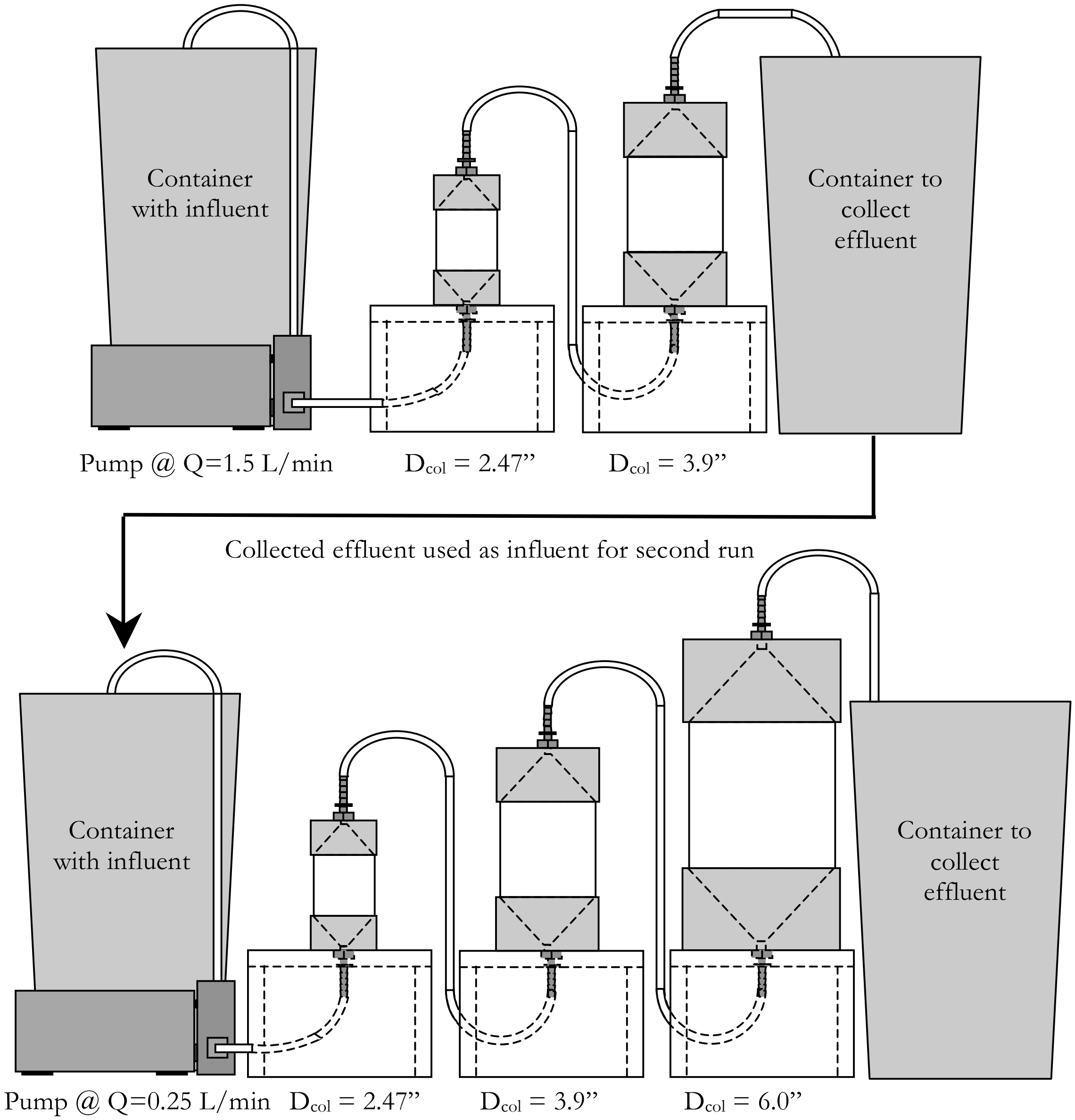


Figure 4.14. Operation of modified elutriation device with two flow rates.

Operating the device using three columns and one flow rate requires less time and effort, but the range of particles measured by the device is not as broad as the distribution determined using three columns with two flow rates. The size range of particles retained in each column if the device is operated at one flow rate is shown in Table 4.2. The range of particles retained if the device is operated with two flow rates is shown in Table 4.3. For both situations the particle size retained is computed by comparing the average upward velocity in the column to the settling velocity of different sized particles. Particles are assumed to be spheres with a specific gravity of 2.65, and temperature is assumed to be 20^{0}C. By changing from one flow rate to two flow rates, the upper range of particles measured increases from 70 to 139 micrometers. The lower range of particles measured decreases from 25 micrometers with one flow rate to 17 micrometers with two flow rates. The importance of the equivalent particle size ranges measured by the modified elutriation device measured is explained at the end of this chapter.

Table 4.2. Range of particles retained in each column with one flow rate

Flow Rate (L/min)	**Column Size (in.)**	**Particle Range (μm)**
0.5	2.5	>70
0.5	4.0	40-70
0.5	6.0	25-40
0.5	Effluent	<25

Table 4.3. Range of particles retained in each column with two flow rates

Flow Rate (L/min)	**Column Size (in.)**	**Particle Range (μm)**
1.5	2.5	>139
1.5	4.0	77-139
0.25	2.5	46-77
0.25	4.0	27-46
0.25	6.0	17-27
0.25	Effluent	<17

4.3.3. Theoretical Adjustment for Multiple Column Elutriation Device

Since the performance of the columns produces results that can be estimated by assuming a laminar flow profile, a correction factor has to be made to estimate the actual settling velocity distribution of particles in the sample. A model to back-calculate results of the device and generate the actual settling velocity distribution was created in Microsoft Excel using Visual Basic for Applications. The program uses the cumulative mass data from the elutriation device and equations about laminar flow to generate the actual distribution.

The first step of the program is inputting the information collected by operating the device at either one or two flow rates. Relevant information includes flow rate, column sizes, water temperature, sample volume, clean water volume, and mass of particles retained in each column. Next, the probability of a particle settling in each column is estimated under the assumption of laminar flow. Table 4.4 shows the probability of a particle landing in one of five columns (two columns at flow rate of 1.5 L/min as indicated by "low", three columns at a flow rate of 0.25L/min as indicated by "high") for a range of particle sizes. The theory and equations used to calculate the distributions are the same used to estimate performance of elutriation devices, which is described in Appendix C.

Table 4.4. Probability of a particle settling in columns of elutriation device

Particle Diameter (μm)	Prob. 2.47" Col. (High)	Prob. 3.9" Col. (High)	Prob. 2.47" Col. (Low)	Prob. 3.9" Col. (Low)	Prob. 6" Col. (Low)	Prob. Effluent (Low)
1	0.01	0.05	0.01	0.04	0.15	0.73
10	0.02	0.06	0.04	0.12	0.28	0.47
20	0.03	0.10	0.13	0.30	0.42	0.01
40	0.10	0.23	0.37	0.30	0.00	0.00
60	0.19	0.41	0.40	0.00	0.00	0.00
80	0.32	0.56	0.12	0.00	0.00	0.00
100	0.47	0.53	0.00	0.00	0.00	0.00
120	0.64	0.36	0.00	0.00	0.00	0.00
140	0.82	0.18	0.00	0.00	0.00	0.00
180	1.00	0.00	0.00	0.00	0.00	0.00
220	1.00	0.00	0.00	0.00	0.00	0.00
270	1.00	0.00	0.00	0.00	0.00	0.00
320	1.00	0.00	0.00	0.00	0.00	0.00
400	1.00	0.00	0.00	0.00	0.00	0.00

Once all the data are input and the probability of specific particles settling in each column are calculated, the program conducts iterations to estimate the actual settling velocity distribution. The mass retained in each column assuming a laminar flow profile is compared to the experimental data to verify the validity of the assumed distribution. The program continues to iterate until the theoretical and actual points are equal. The Solver subroutine in Microsoft Excel is used to adjust the assumed distribution and minimize the difference between expected and experimental results. A more thorough explanation of the program and the written code are provided in Appendix G.

Figure 4.15 shows results created by the program. For this example the Li *et al.* (2005) distribution is used as the "Actual Distribution," and the elutriation device is assumed to be operating with the two sets of columns at flow rates of 1.5 L/min and 0.25 L/min. The results of the presumed experimental runs would then be the square dots, which would then be used in the spreadsheet program to compute the estimated distribution.

As demonstrated in Figure 4.15, the program can accurately estimate the actual distribution from the points generated by operating three columns at two different flow rates. The main source of error with the program is estimating the distribution of particles larger than the maximum velocity measured in the elutriation device. The only way to mitigate the error is either by estimating the shape of the distribution of particles with settling velocities larger than the maximum settling velocity measured or to sieving the larger particles as desired to include in the distribution. Adding additional columns or operating the device at higher flow rates can also increase the maximum settling velocity measured.

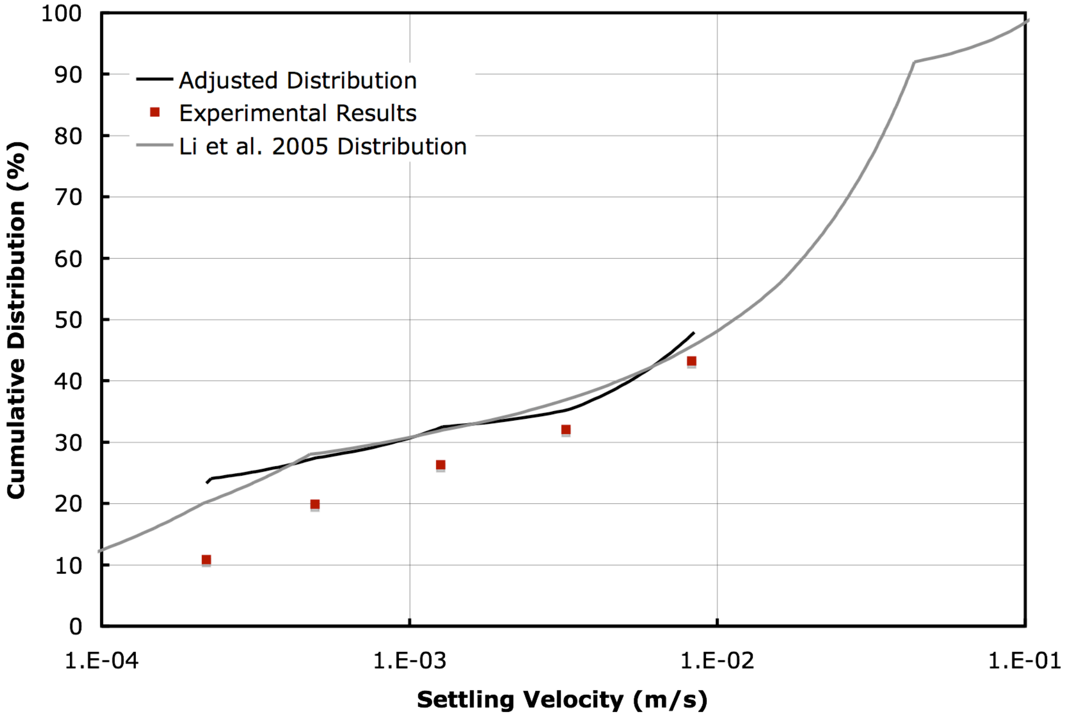


Figure 4.15. Results for program calculating actual settling velocity distribution. The device is assumed to operate at 1.5 L/min and 0.25 L/min.

4.3.4. Results from Modified Elutriation Device

The methods described in the previous section were used to test the modified elutriation device. The device was first operated with flow rates of 1.5 L/min for the 2.47 inch (63 mm) and 3.9 inch (99 mm) columns. The effluent from this experiment was collected and pumped through all three columns at a flow rate of 0.25 L/min. The results from the device are summarized in Table 4.5.

Table 4.5. Results from modified elutriation device

Flow Rate (L/min)	Column Size (in.)	Mass Retained (g)	Mass Retained (%)
1.5	2.47	1.261	28.3
1.5	3.9	1.307	29.4
0.25	2.47	0.801	18.0
0.25	3.9	0.421	9.5
0.25	6.0	0.327	7.4
Effluent	-	0.331	7.4

The results from the experimental run were input into the program described in the previous section. Results from the program are shown in Figure 4.16 and are compared with the actual settling velocity distribution. The actual settling velocity distribution is estimated using the known particle size distribution and the Ferguson and Church settling velocity equation. The points measured from the elutriation device fall below the adjusted distribution because particles are retained in each column in a manner that mimics a laminar flow profile. The portion of the adjusted distribution curve less than the minimum upward column velocity and greater than the maximum upward column velocity are not provided in the figure, but the settling velocity curves outside the range can be estimated and extrapolated if necessary.

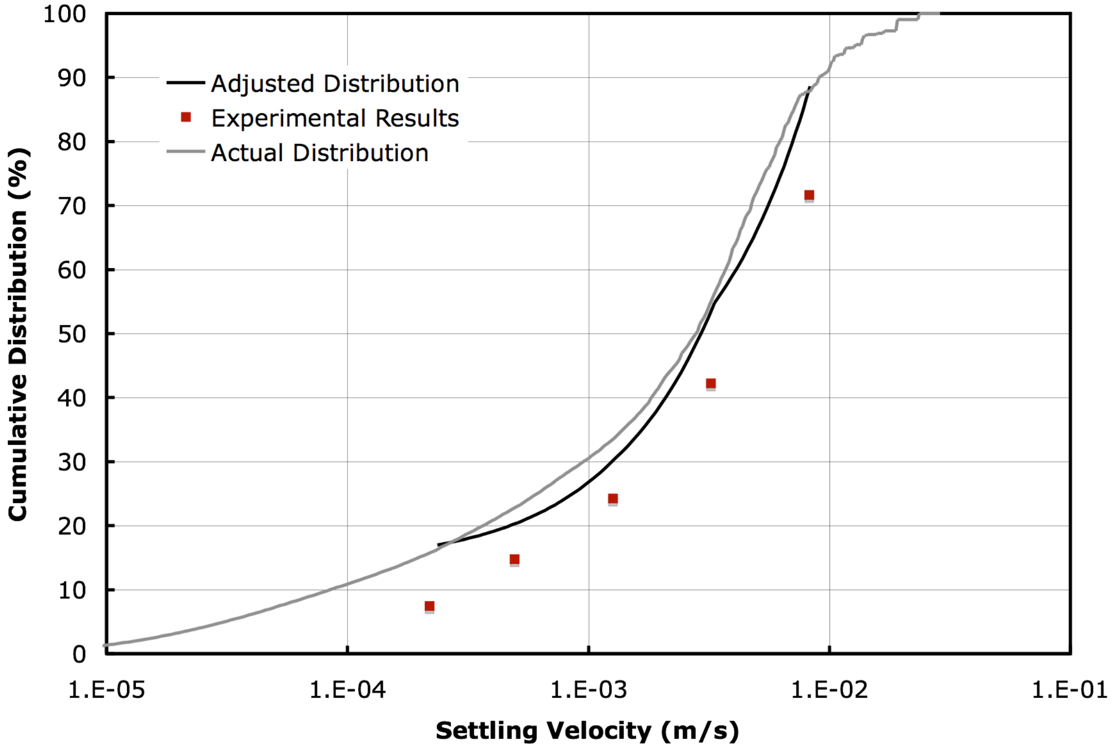


Figure 4.16. Adjusted results from operation of modified elutriation device. The device was operated at 1.5 L/min with the two smallest columns and 0.25 L/min with all three columns.

As shown in Figure 4.16, the adjusted settling velocity distribution lies very close to the actual settling velocity distribution. The results demonstrate the theoretical model can effectively back-calculate from the actual elutriation device results to the actual settling velocity distribution. The elutriation device coupled with the program can act as another tool to measure settling velocity distribution of particles in stormwater runoff.

4.4. Importance of Size Ranges Measured by Modified Elutriation Device

Since the columns of the modified elutriation device are interchangeable and the peristaltic pump can adjust the flow rates through the columns, a large range of settling velocities can be investigated. As mentioned in the previous section, operating the elutriation device at a single flow rate of 0.5 L/min allows particles between 25 and 70 micrometers to be measured. If the device is operated with two flow rates of 1.5 L/min and 0.25 L/min, the range of particles measured by the device increases to between 17 and 139 micrometers. The particle sizes measured by the device are important because particles less than the minimum size measured generally cannot be removed by settling devices. Conversely, the particles larger than the maximum size measured are very efficiently removed from settling devices. If desired the size distribution for these larger sizes can readily be estimated by wet sieving (ASTM C117-04).

Figure 4.17 demonstrates the removal efficiency for a well-mixed pond that is 0.25 percent of the watershed area. If the pond were treating a contributing watershed area of 3 acres (1.21 hectares), the pond would be 325 square feet (30 square meters) in area. A pond of this size effectively removes particles greater than 70 and 130 micrometers, but it is not very efficient at removing particles less than 25 and 17 micrometers. The same relationship is true for a hydrodynamic separator, which is shown in Figure 4.18. In the figure the hydrodynamic separator is assumed to be working at 100 percent of its recommended maximum flow rate. If knowledge about the settling velocity distribution of particles between efficient and inefficient removal is known, the actual removal of particles from the device can be estimated.

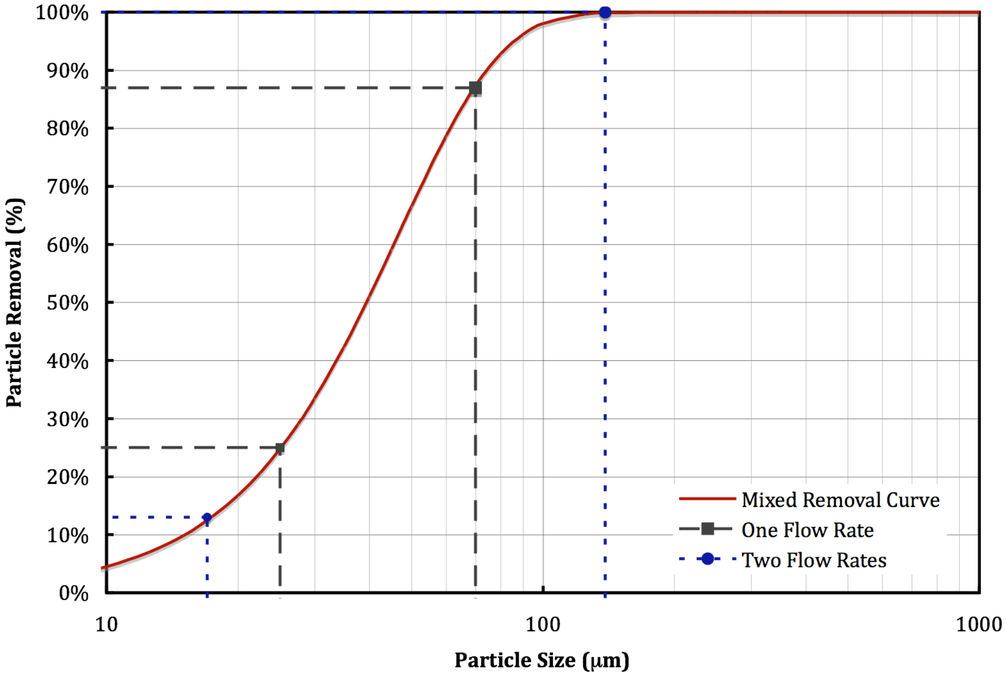


Figure 4.17. Particle removal efficiency for well-mixed pond. The black and blue lines indicate the range of particle sizes for one and two flow rates, respectively.

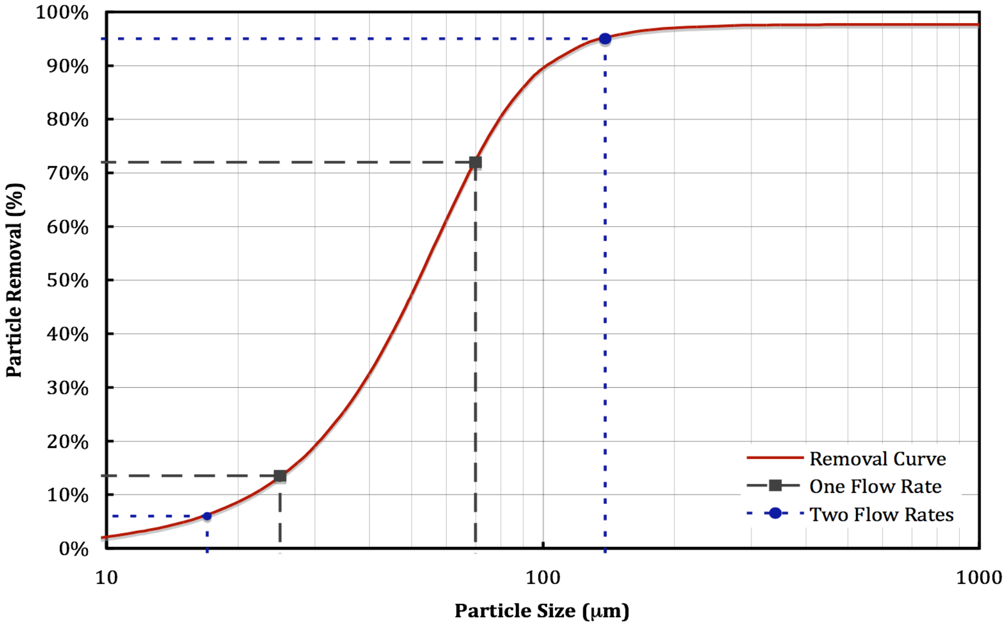


Figure 4.18. Particle removal efficiency for hydrodynamic separator. Black and blue lines indicate the range of particle sizes for one and two flow rates, respectively.

While the elutriation device is effective at measuring the important range of particles required to calculate particle removal from various devices, knowledge about the rest of the mass is required. The elutriation device should be coupled with simple sieving to more effectively characterize the larger particles. Before a stormwater sample is passed through the device, it should be wet-sieved through a series of sieves ranging from 500 micrometers (No. 35 sieve) down to 149 micrometers (No. 100 sieve). First, the dried mass retained on each sieve can be measured. Next, a volatile suspended solids test could be performed to determine how many organics are associated with each size range. Densities for the organic and inorganic particles can be assumed, and the settling velocity distribution for the larger particles can be calculated. This particle size distribution can be combined with the settling velocity distribution measured by the elutriation device for a more complete picture of the overall settling velocity distribution.

5. Discussion and Conclusions

This thesis focused on research about particle size distribution and particle settling velocity distribution in runoff and the importance of the parameters in unit operation design. Additionally, the concept of elutriation to determine settling velocity distribution for particles in urban stormwater applications is discussed. The two areas are directly related, and modified elutriation devices may help develop standard protocols for the evaluation of particle settling velocity in stormwater.

5.1. Advantages and Disadvantages of Modified Elutriation Device

The modified elutriation device has distinct advantages over other methods used to measure particle size distribution and particle settling velocity distribution of particles in runoff. First, the device directly measures settling velocity so assumptions about particle shape, texture, and density are not required to calculate settling velocity. Second, the device is relatively cheap and easy to manufacture. The column is assembled from plastic tubing, the top and bottom caps can range from machined aluminum to rubber stoppers with plastic columns, and the tubes between columns and their connectors can be purchased at any home improvement store. Third, the device is simple to operate. Once the device is set up, the operator only has to turn on the pump.

Another advantage of the modified elutriation device is the flexibility of its application. Since the device has numerous columns and can be operated at various flow rates, the potential range of settling velocity distributions measured varies significantly. The device can be operated with columns and flow rates that can be specifically adjusted based on different applications. As described in Chapter 4, the standard operation of the modified elutriation device provides a settling velocity distribution range that is important in the design of treatment practices utilizing sedimentation as the main source of particle removal.

Although the elutriation device has some positive features, it does have some disadvantages. The most notable disadvantage of the device is the inability to obtain a truly uniform flow profile through the columns. Since the particles retained in the device mimic what is expected from a laminar flow profile, however, the results from the device can be theoretically back-calculated to determine the true settling velocity distribution. Another disadvantage of the device is the amount of stormwater required for operation. Generally, the device requires at least a ten-liter sample to obtain a single result. Finally, the analysis of the samples once the device has operated can be time and labor intensive. As mentioned above, the operation of the device is very hands-off while it is operating. Once the device finishes, however, water and sediment must be independently collected from each column and the effluent. The total mass of the particles is determined by either a TSS or SSC test, which requires a large portion of time to filter the water/sediment mixture through a small filter.

Despite its drawbacks, the modified elutriation device is a useful tool for determining settling velocity distribution of particles in urban stormwater runoff. A detailed explanation of the potential applications for the modified elutriation devices is provided in the following section.

5.2. Current Sampling and Analysis Methods

Although a body of knowledge has been formed regarding the particle size distribution of particles in urban stormwater runoff, most of the results cannot be directly compared or used at other sites. The main shortcoming of the past three decades of particle size distribution measurement and sampling is the lack of effective, standard protocols for research. The issue must be addressed if future research and monitoring is to be effective and produce useful, transferable data.

5.2.1. Protocol for Sample Collection

Studies about particle size distribution in urban settings generally look at particles collected directly from source surfaces or from outfalls during rainfall events. The particle size distribution and particle settling velocity distribution of particles from the two methods vary greatly because many other factors are involved in the transport of particles from a street surface to the outfall. As a result, sample collection methods must be refined to ensure standard, reproducible results.

5.2.1.1. Collection of street surface particles versus outfall sampling

Collection of street surface particles and monitoring of runoff have both been used to characterize the particle size distribution of particles in urban watersheds. Minton and Sutherland (2010) argue that collecting street surface particles rather than sampling runoff is a more reasonable approach when gathering information about particles in a watershed because characterizing particle size distribution from urban runoff can be problematic. For example, results from the NURP studies indicate settling velocity distribution of particles in runoff have significant storm-to-storm variation (USEPA 1986). Therefore, in order to determine a statistically significant representative distribution at a specific site, a large number of samples over a large number of storms would have to be collected. Similarly, Minton and Sutherland (2010) observe runoff studies are expensive so they are typically only implemented at a few sites. The few sites are often selected on the basis of accessibility and not how well the outfall represents the rest of the watershed. Runoff sampling is also problematic because a large volume of stormwater must be collected to gather a large mass of particles.

Minton and Sutherland (2010) advocate collecting street-surface particles using vacuums or street-sweepers because the method eliminates many of the problems associated with sampling runoff. Collection of street-surface particles is relatively inexpensive and simple to implement. As a result, numerous samples can be collected at many sites at any time during the year. The methods also provide an easier mechanism to collect a large amount of particle mass without having to collect the corresponding stormwater.

Using only street-surface particles, however, has limitations. First, collection and analysis of street-surface particles only provide information about the source of the materials and do not provide information about the effectiveness of various management practices. Additionally, the transport of particles from street-surfaces to a receiving water body depends on many features including upstream treatment devices, pipe slopes, and flow characteristics so it is difficult to predict what particle size distribution will actually be exiting at a specific outfall. Finally, street-surface particles provide no information about the dissolved pollutants that occur during a rainfall event. Dissolved pollutants are easily transported in the environment so their characterization is important.

5.2.1.2. Protocols for sampling urban stormwater Runoff

The various methods used to collect runoff samples vary widely and have a measurable impact on particle size distribution. Automatic sampling methods are convenient, but the particle size distribution sampled depends on the location of the sampling manifold in the outfall pipe. Conversely, grab sampling collects particles from the entire flow cross-section, but it is very time and labor intensive to collect samples. The other method discussed, Lateral Pavement Sheet Flow, collects the entire distribution washed off from a street surface, but it requires collection of thousands of liters of stormwater. The sampling methods have their respective advantages and disadvantages, but the particle size distribution sampled by each method will be different.

To adequately compare results from different studies, standard stormwater collection techniques must be developed for widespread implementation. Until automatic sampling technology improves, the use of automatic samplers when characterizing particle size distribution may not be appropriate. One option to improve automatic samplers is improving the intake so it collects stormwater samples at various points across the flow cross-section rather than one single point within the pipe (DeGroot and Gulliver 2009). Kayhanian *et al.* (2005) also present a modification to the existing sampling manifold to improve sampling accuracy. The manifold is mounted on a block that lifts with increasing flow depth so it is always located in the center of the flow column.

5.2.2. Protocol for Studies Measuring Particle Size Distribution

Li *et al.* (2005) conducted experiments to begin the development of a protocol for proper handling of stormwater samples meant for particle size distribution analysis. The protocol addresses four main components: Particle size distribution reproducibility, sample contamination, sample representativeness, and sample storage time and temperature. The major points are briefly described below, and the protocol is similarly summarized in Kayhanian *et al.* (2005).

1) PSD reproducibility: An equation to calculate a parameter called difference proportion can be used to quantify the difference between duplicate samples.
2) Sample contamination: Using hand washed glass bottles can prevent the potential of sample contamination.
3) Sample representativeness: A simple inversion technique can provide effective mixing of the sample without destroying fragile flocs.
4) Storage time and temperature: All samples should be analyzed within six hours of collection because particles in stormwater tend to naturally aggregate.

In addition to standard handling methods and procedures, a detailed protocol for measuring particle size distribution must be established. The advantages and limitations of the various particle-sizing techniques are discussed in Chapter 2. To obtain a full particle size distribution, a combination of the methods should be utilized. For particles larger than approximately 150 - 500 micrometers, using sieving techniques to measure particle size distribution is a good option. For smaller particles, however, the electric resistivity devices or laser sizing devices can be used to get a more refined distribution for the smaller particle sizes.

5.2.3. Role of Modified Elutriation Device in Future Urban Runoff Studies

While early studies concerning particles in urban runoff focused primarily on obtaining a particle settling velocity distribution, most recent studies focus primarily on characterizing a particle size distribution. The important parameter when designing management practices utilizing sedimentation, however, is settling velocity, and particle size only serves as a proxy to estimate settling velocity. Settling velocity from particle size requires knowledge about particle properties such as density, shape, and texture. These properties are frequently unknown, and the importance of assumptions about them is often overlooked. The oversight may contribute to inappropriate design of unit operations to treat stormwater runoff.

The modified elutriation device has potential for furthering the understanding of settling velocity distributions in urban stormwater runoff. Since it is easy to use and cheap to manufacture, many practitioners and researchers at various sites to measure site-specific settling velocity distribution can use the elutriation device. Site-specific information will allow for more refined and accurate design of stormwater management practices. Additionally, the settling velocity distributions along with information about site and storm characteristics can be collected in a database. If enough data is generated, trends relating settling velocity distribution to different characteristics could be computed. The trends could ultimately lead to better estimation of settling velocity distribution at various locations.

The elutriation device can also be utilized to gather information about pollutant properties. Previous researchers have shown the pollutant concentration on particles is related to the size of the particles (Sansalone *et al.* 1997). Directly applying the results of the experiments to predict the performance of stormwater management practices relying on settling velocity as the primarily removal mechanism is problematic, however. For example, if metal fragments from vehicle wear fit into a specific size range, it will contribute to the metal concentrations in that size range. If the settling velocity for the size range is computed with an assumed specific gravity for soils (e.g. 2.65), the settling velocity of the metal fragments will be underestimated because the metal fragments have a higher specific gravity. The elutriation device overcomes this issue because it fractionates the particles into actual settling velocity ranges. Once the particles are fractionated, the pollutant concentrations of the particles in each of these ranges can be determined. The information can then be applied to design for stormwater management practices to predict pollutant removal.

5.3. Particle Distributions in Urban Stormwater Monitoring

Research investigating particle properties, particle size distribution, particle settling velocity, and particle transport as they relate to stormwater management must continue to be developed. As more standardized protocols are established and more information is collected, design and implementation of efficient treatment strategies will continue to improve. Nonetheless, critical evaluation about the validity of various stormwater monitoring practices must be undertaken. The modified elutriation device can play a role in the further refinement of methods to ensure stormwater monitoring projects are more effective and applicable.

6. References

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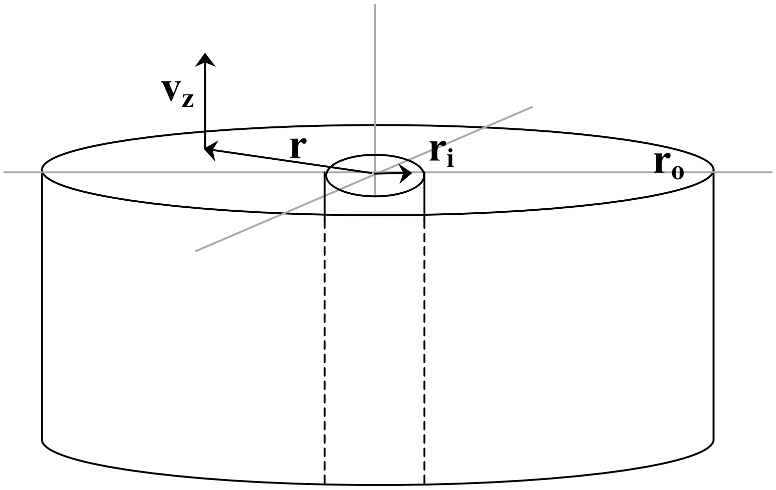
Appendix A. Derivation for Laminar Flow Profile through Annulus

Adapted from Munson et al. 2006



- **Assumptions:**
  - Flow is parallel to walls
    $v_r = 0$, $v_\theta = 0$
  - Velocity is zero at walls
    $v_z = 0$ @ $r = r_i$ and R
  - From Continuity
    $\frac{\partial v_z}{\partial z} = 0$
  - Gravity only acts in horizontal direction
    $g_r = 0$, $g_q = 0$, $g_z = g$

- **Simplified Navier-Stokes Equations**

$$0 = -\frac{\partial p}{\partial r}$$ Equation A.1

$$0 = -\frac{1}{r} * \frac{\partial p}{\partial \theta}$$ Equation A.2

$$0 = -\frac{\partial p}{\partial z} + \rho g + \mu\left[\frac{1}{r} * \frac{\partial}{\partial r}\left(r * \frac{\partial v_z}{\partial r}\right)\right]$$ Equation A.3

- **Solutions**
  - Integrating Equations A.1 and A.2
    $p = f_1(z)$ Equation A.4
  - Solve for Equation A.3

$$\left[\frac{1}{r} * \frac{\partial}{\partial r}\left(r * \frac{\partial v_z}{\partial r}\right)\right] = \frac{1}{\mu} * \frac{\partial p}{\partial z} - \frac{\rho g}{\mu}$$

- Integrate with respect to r

$$r\frac{\partial v_z}{\partial r} = \frac{1}{2\mu}\left(\frac{\partial p}{\partial z}\right)r^2 - \frac{\rho g}{2\mu} * r^2 + C_1$$

- Integrate again with respect to r

$$v_z = \frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)r^2 - \frac{\rho g}{2\mu} * r^2 + C_1 \ln(r) + C_2$$

- Solve for C_1 and C_2 knowing, $v_z = 0$ at $r = r_i$ and r_o

$$0 = \frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)r_o^{\ 2} - C_1 \ln r_o^{\ 2} + C_2$$

$$0 = \frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)r_i^2 - C_1 \ln r_i^2 + C_2$$

$$C_1 = \frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)\left[r_i^2 - r_o^{\ 2}\right] * \frac{1}{\ln\left[r_o/r_i\right]}$$

$$C_2 = -\frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right) * r_o^{\ 2} + C_1 * \ln\left[r_o\right]$$

- Velocity distribution becomes

$$v_z = \frac{1}{4\mu}\left(\frac{\partial p}{\partial z} + \rho g\right)\left[r^2 - r_o^{\ 2} + \frac{r_i^2 - r_o^{\ 2}}{\ln\left(r_o/r_i\right)} * \ln\frac{r}{r_o}\right] \qquad \text{Equation A.5}$$

- Find relationship between Q and pressure gradient dA = (2πr)dr between r_i and r_o

$$dQ = v_z(2\pi r)dr$$

$$Q = 2\pi \int_{r_i}^{r_o} v_z * r * dr$$

- Solve for Q

$$Q = 2\pi \int_0^R \left[\frac{1}{4\mu}\left(\frac{\partial p}{\partial z} + \rho g\right)\left[r^2 - r_o^{\ 2} + \frac{r_i^2 - r_o^{\ 2}}{\ln\left(r_o/r_i\right)} * \ln\frac{r}{r_o}\right] * r\right]dr$$

$$\boxed{Q = -\frac{\pi}{8\mu}\left(\frac{\partial p}{\partial z} - \rho g\right)\left[r_o^{\ 4} - r_i^{\ 4} - \frac{\left(r_o^{\ 2} - r_i^2\right)^2}{\ln\left(r_o/r_i\right)}\right]} \qquad \text{Equation A.6}$$

- Δp occurs over a length l

$$\frac{\Delta p}{l} = -\frac{\partial p}{\partial z}$$

- Therefore

$$\boxed{Q = \frac{\pi}{8\mu}\left(\frac{\Delta p}{l} + \rho g\right)\left[r_o^{\ 4} - r_i^{\ 4} - \frac{\left(r_o^{\ 2} - r_i^2\right)^2}{\ln\left(r_o / r_i\right)}\right]} \qquad \text{Equation A.7}$$

- Rearranging Equation A.7

$$\left(\frac{\Delta p}{\mu l} + \frac{\rho g}{\mu}\right) = \left(\frac{8}{\pi} * Q\right)\left(\frac{1}{\left[r_o^{\ 4} - r_i^{\ 4} - \frac{\left(r_o^{\ 2} - r_i^2\right)^2}{\ln\left(r_o / r_i\right)}\right]}\right) \qquad \text{Equation A.8}$$

- Rearranging and simplifying Equation A.5

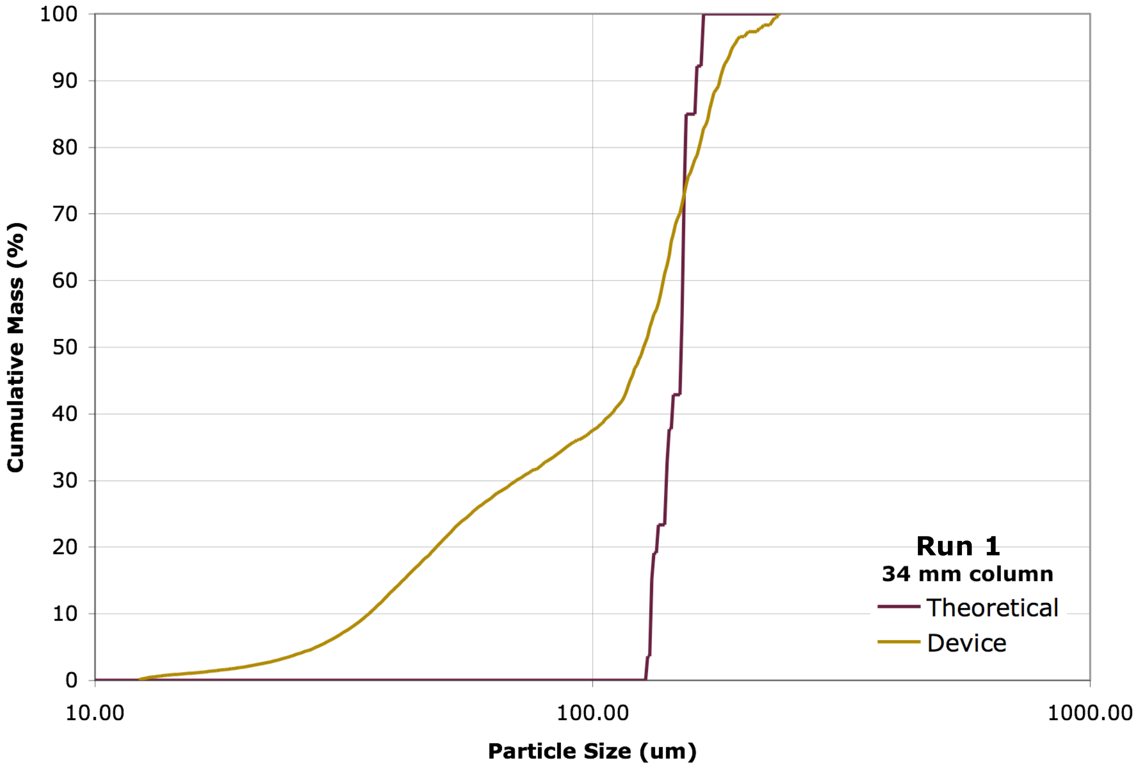
$$v_z = \frac{1}{4\mu}\left(\frac{\Delta p}{l} + \rho g\right)\left[r^2 - r_o^{\ 2} + \frac{r_i^{\ 2} - r_o^{\ 2}}{\ln\left(r_o / r_i\right)} * \ln\frac{r}{r_o}\right] \qquad \text{Equation A.9}$$

- Combining Equation A.8 and Equation A.9

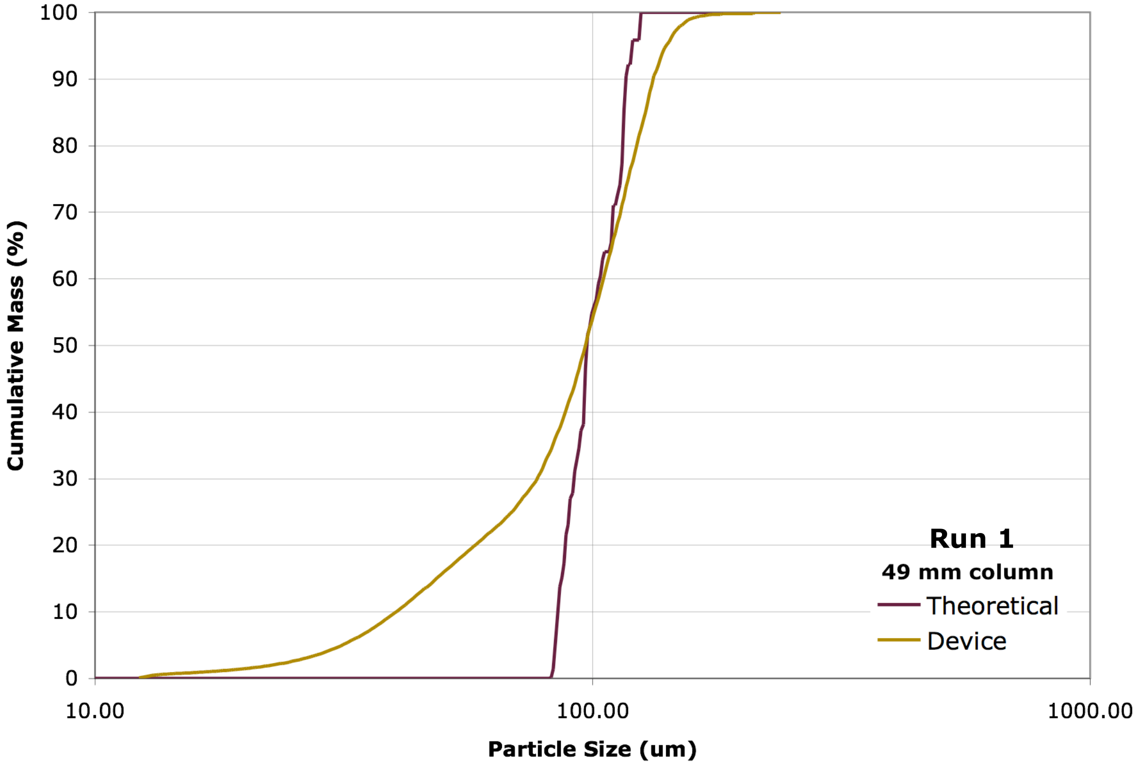
$$\boxed{v_z = \frac{2}{\pi} * Q * \frac{\left[r^2 - r_o^{\ 2} + \frac{r_i^{\ 2} - r_o^{\ 2}}{\ln\left(r_o / r_i\right)} * \ln\frac{r}{r_o}\right]}{\left[r_o^{\ 4} - r_i^{\ 4} - \frac{\left(r_o^{\ 2} - r_i^2\right)^2}{\ln\left(r_o / r_i\right)}\right]}} \qquad \text{Equation A.10}$$

Appendix B. Results for Environment Canada Device

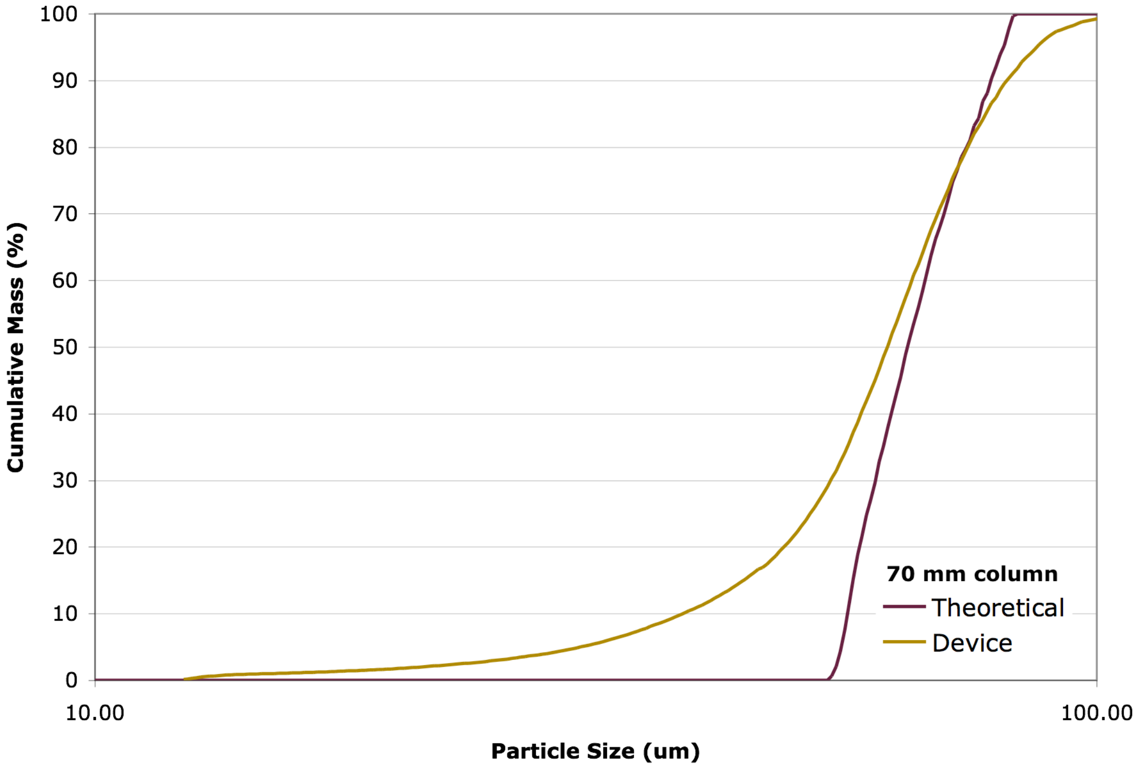
The Environment Canada elutriation device was tested using particles with a known size distribution and density. After particles were pumped through the six columns, they were collected so the size distribution of the particles retained in each column could be measured using a coulter counter. The following figures show the particle size distribution of particles in each column compared to the expected particle size distribution when a uniform velocity profile is assumed. Figures for four different experimental runs are included, and each run includes a total of seven distributions.



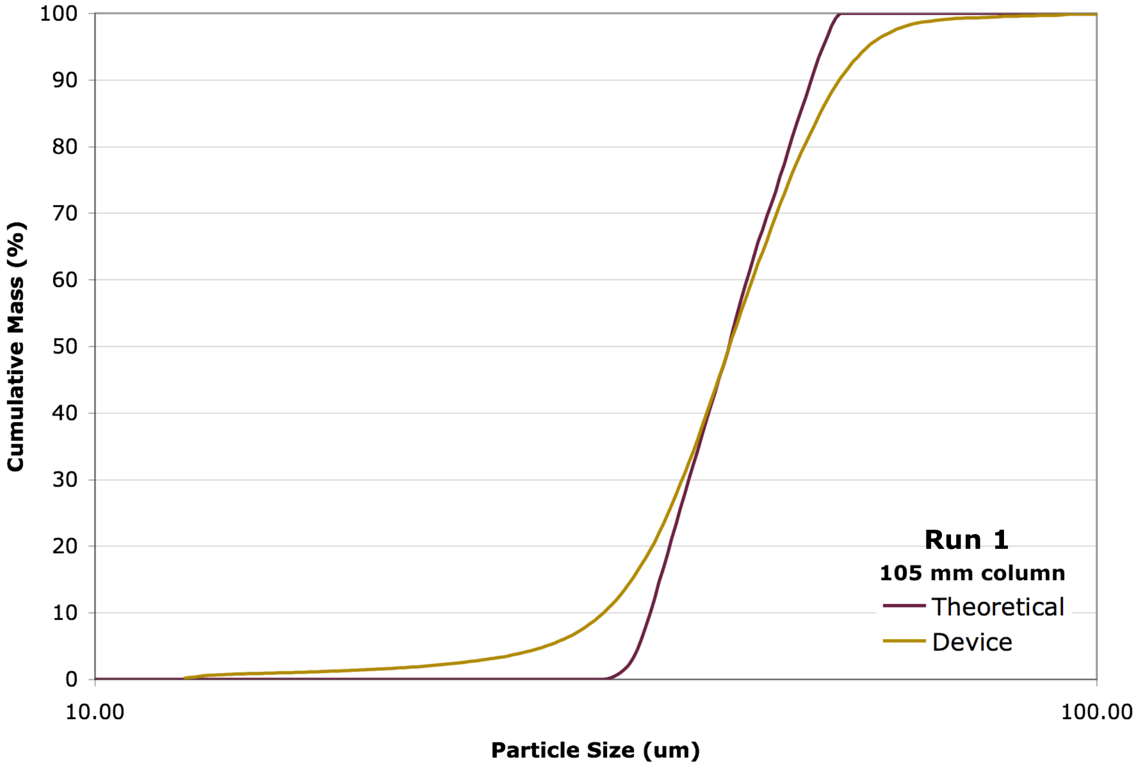
100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10.00
100.00
1000.00
Particle Size (um)
Run 1
34 mm column
Theoretical
Device



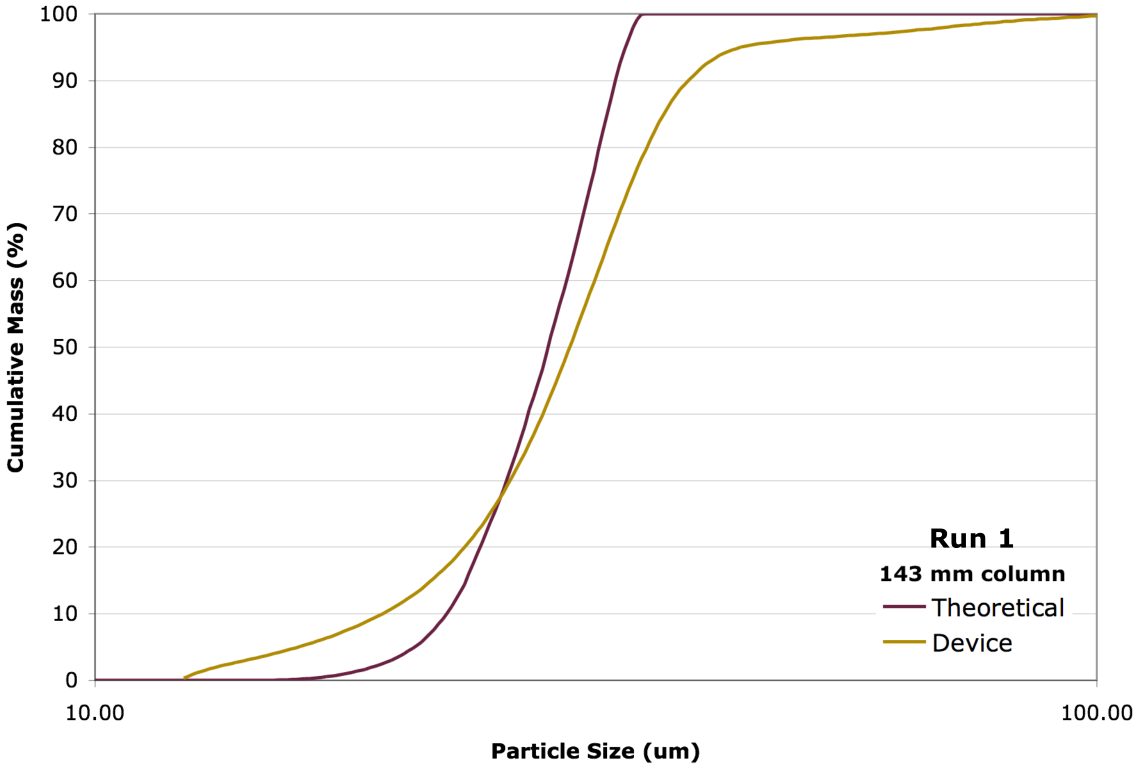
100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10.00
100.00
1000.00
Particle Size (um)
Run 1
49 mm column
Theoretical
Device

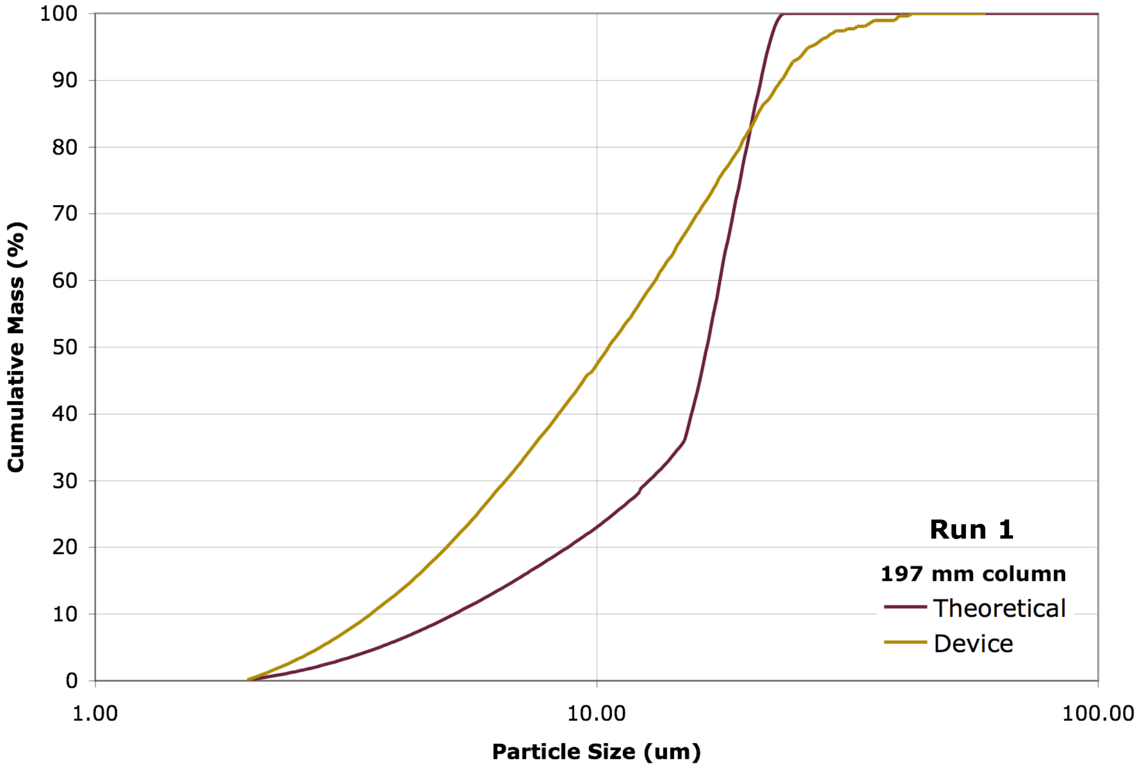


100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10.00
100.00
Particle Size (um)
70 mm column
Theoretical
Device



100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10.00
100.00
Particle Size (um)
Run 1
105 mm column
Theoretical
Device


100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10.00
100.00
Particle Size (um)
Run 1
143 mm column
Theoretical
Device


100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
1.00
10.00
100.00
Particle Size (um)
Run 1
197 mm column
Theoretical
Device

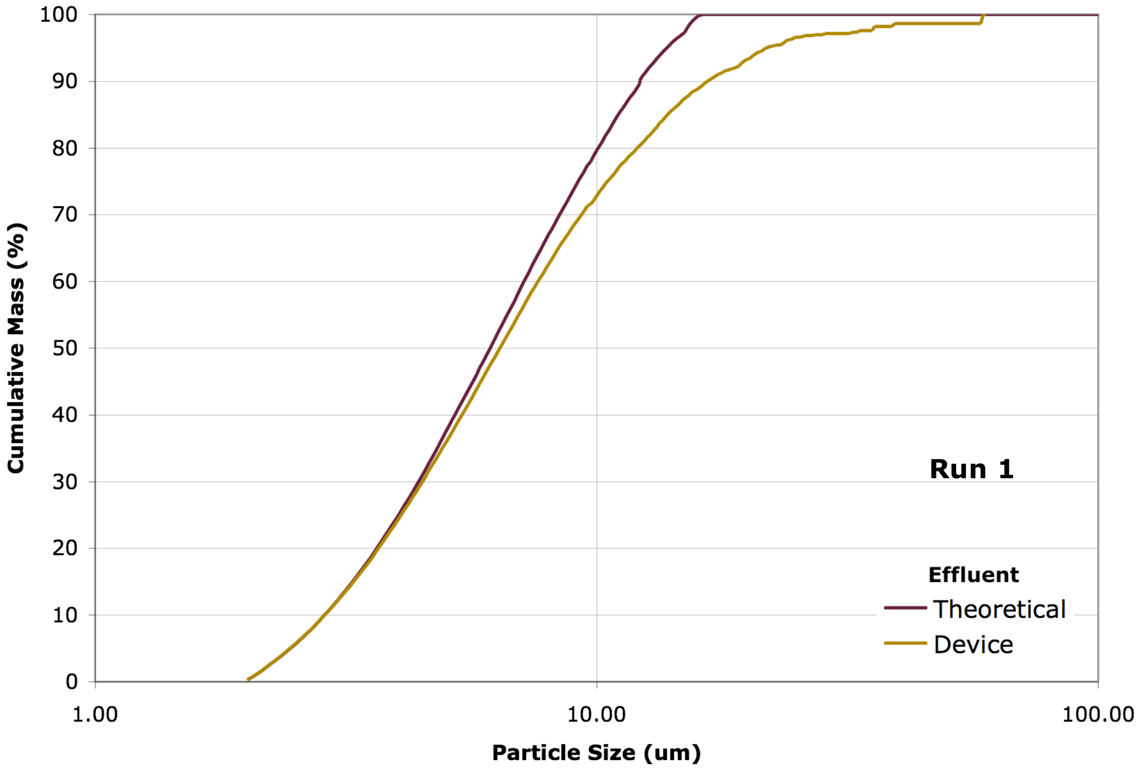
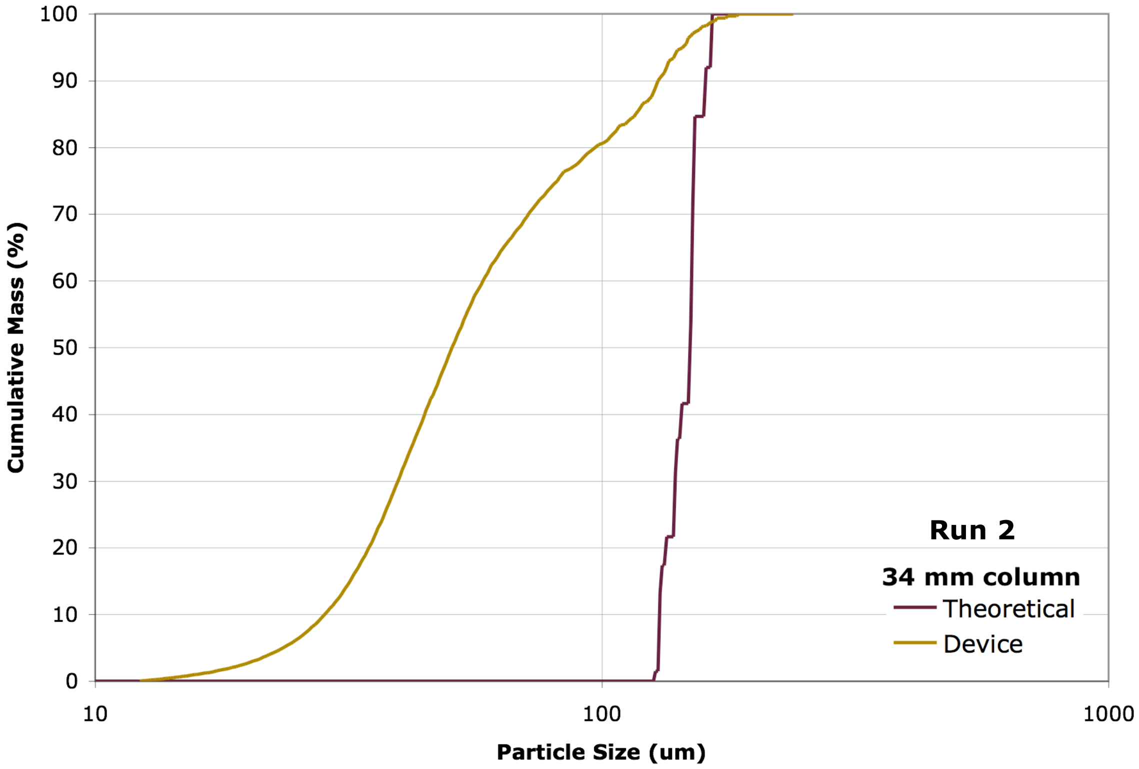
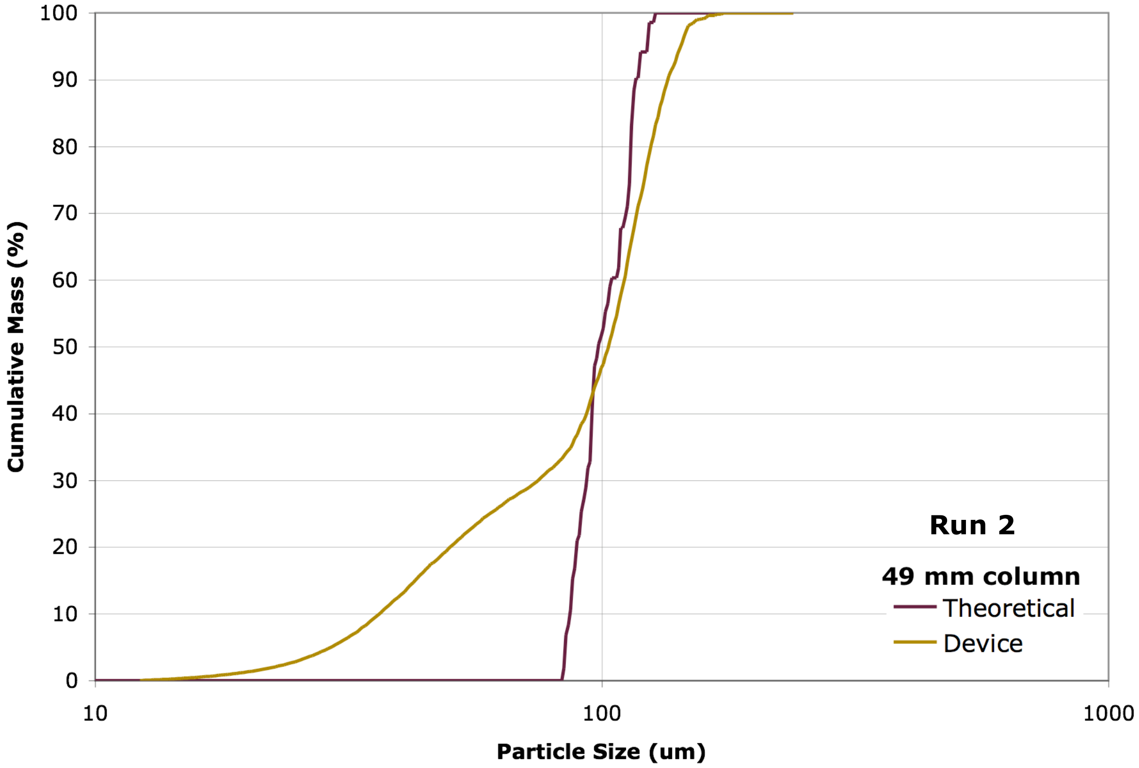
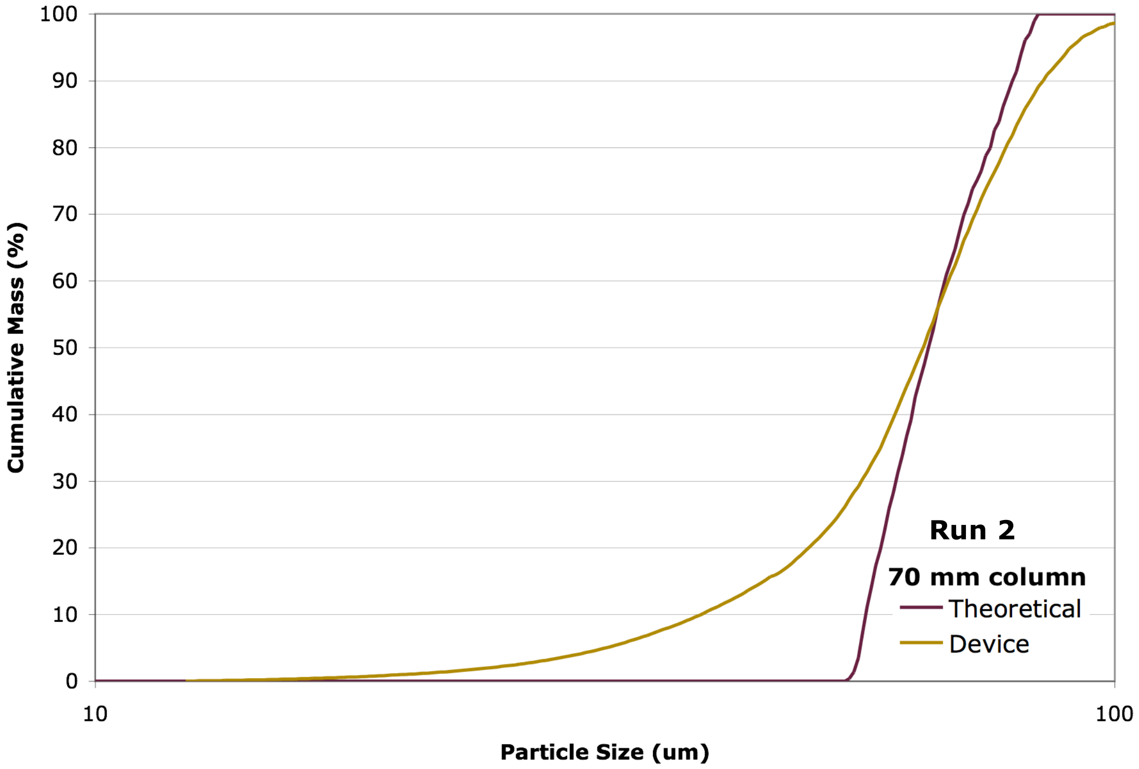
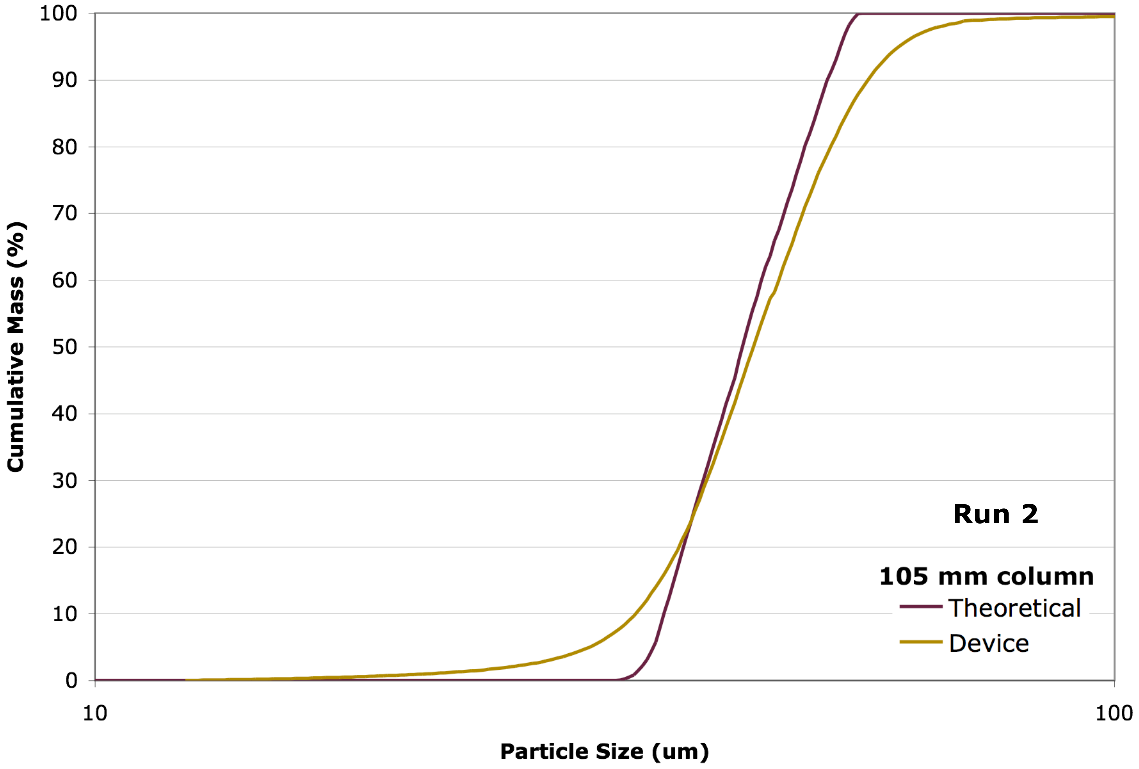


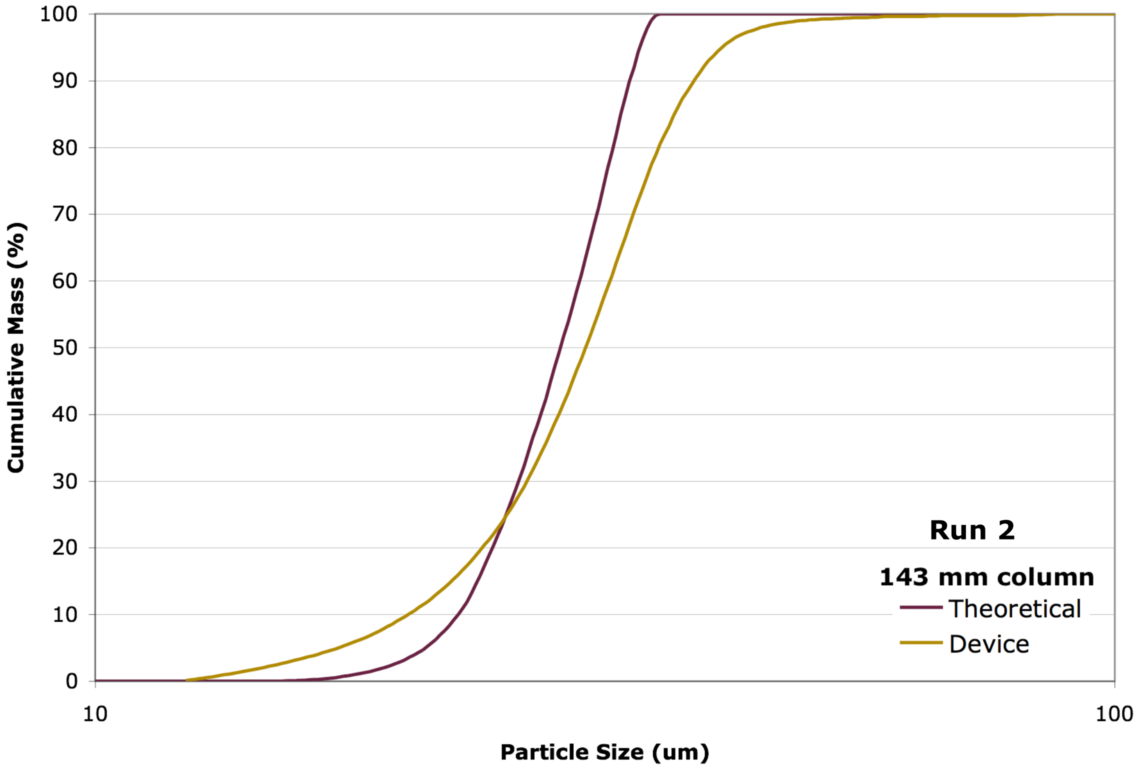
Figure B.1. Run 1 comparison of particle size distributions retained in each column versus uniform flow profile


Cumulative Mass (%)
100
90
80
70
60
50
40
30
20
10
0
10
100
1000
Particle Size (um)
Run 2
34 mm column
Theoretical
Device

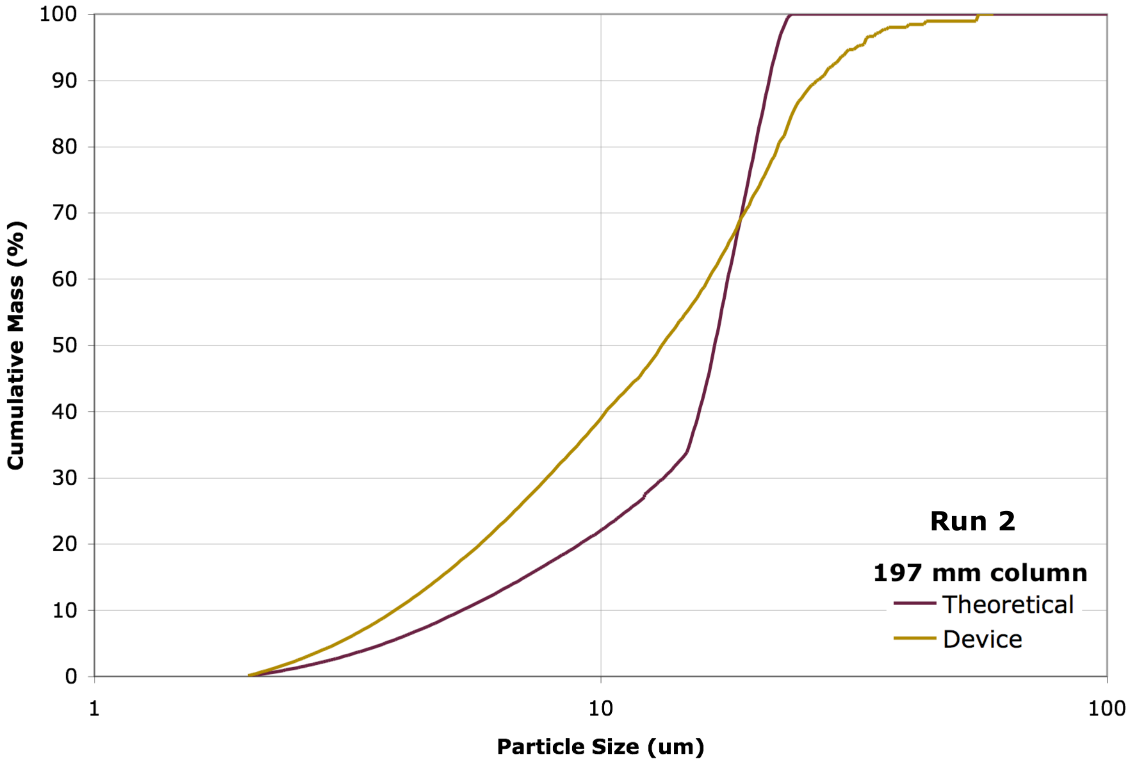

Cumulative Mass (%)
100
90
80
70
60
50
40
30
20
10
0
10
100
1000
Particle Size (um)
Run 2
49 mm column
Theoretical
Device


Cumulative Mass (%)
100
90
80
70
60
50
40
30
20
10
0
10
100
Particle Size (um)
Run 2
70 mm column
Theoretical
Device


Cumulative Mass (%)
100
90
80
70
60
50
40
30
20
10
0
10
100
Particle Size (um)
Run 2
105 mm column
Theoretical
Device



100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10
100
Particle Size (um)
Run 2
143 mm column
Theoretical
Device



100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
1
10
100
Particle Size (um)
Run 2
197 mm column
Theoretical
Device

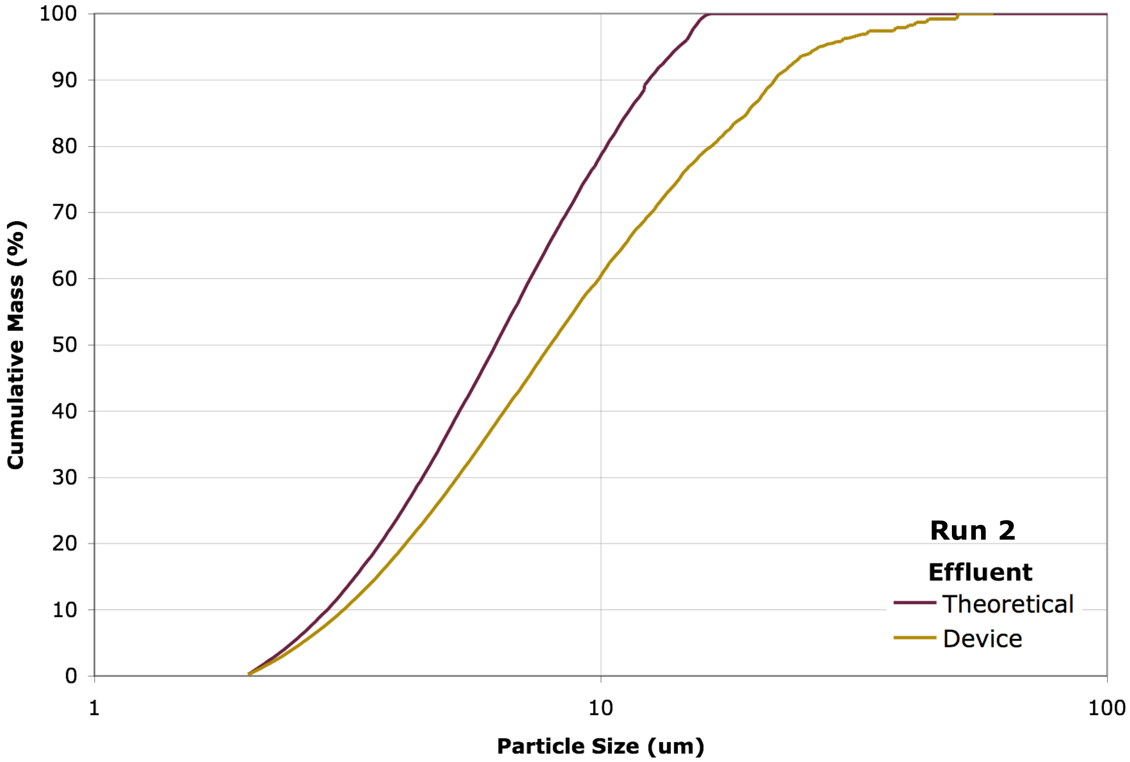
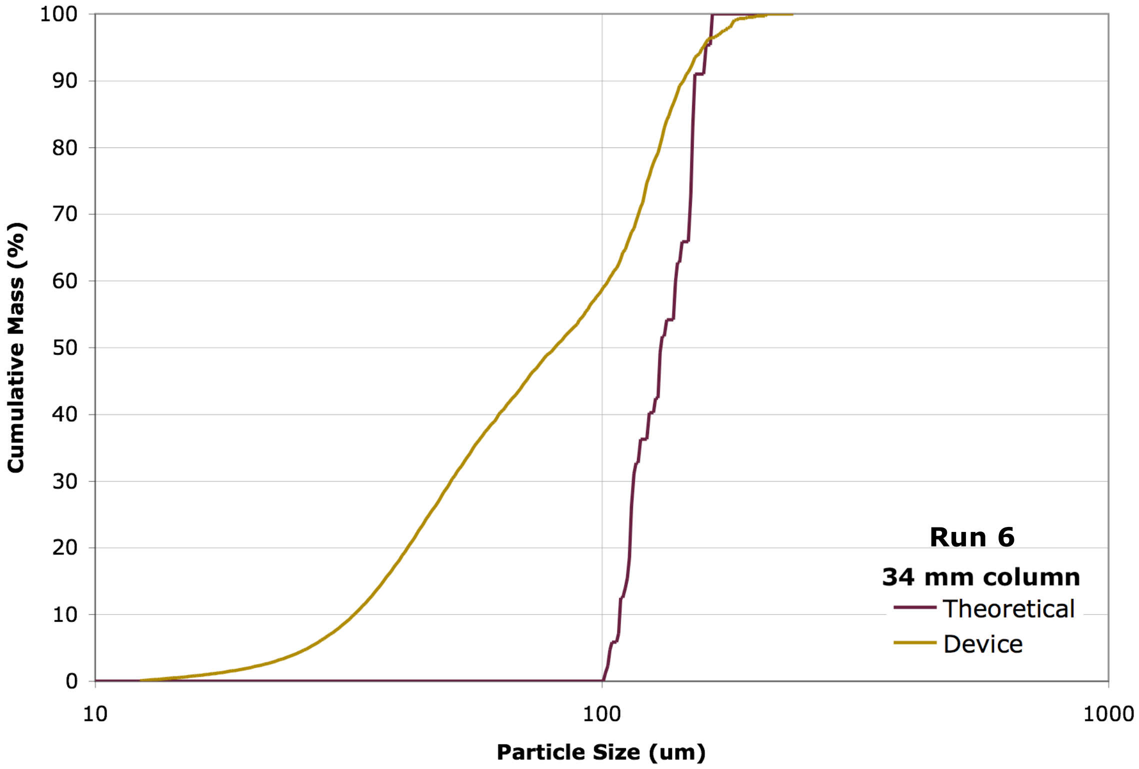
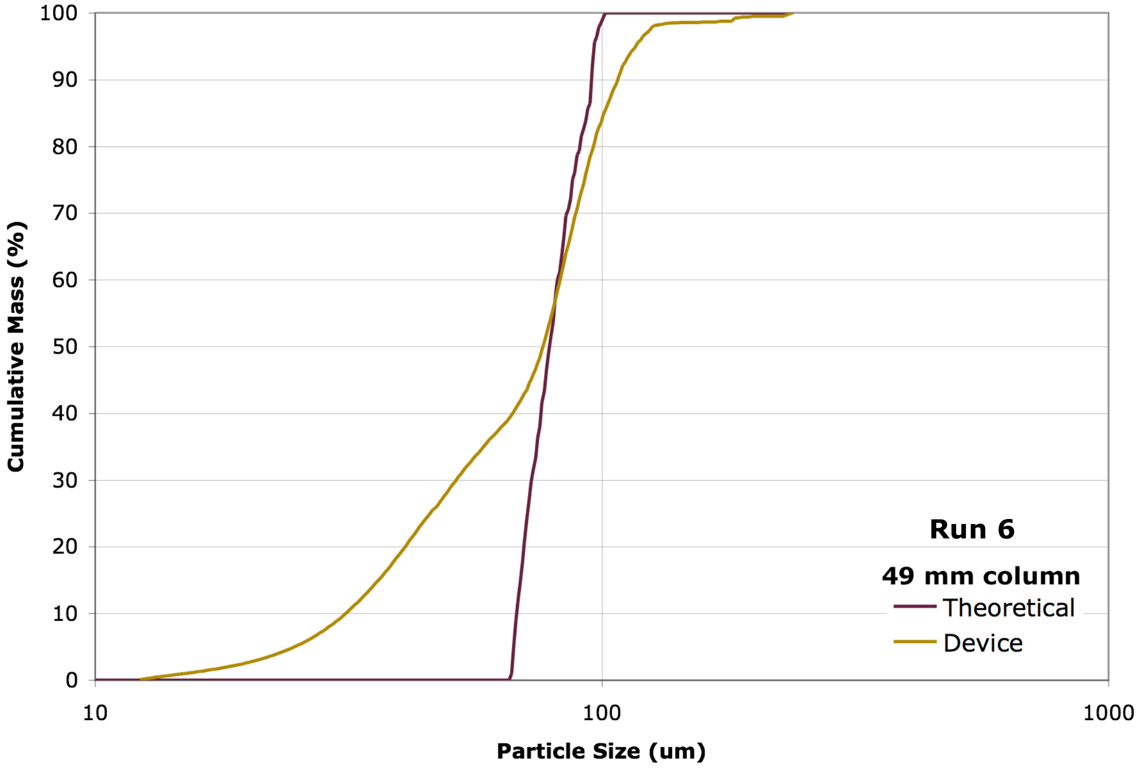


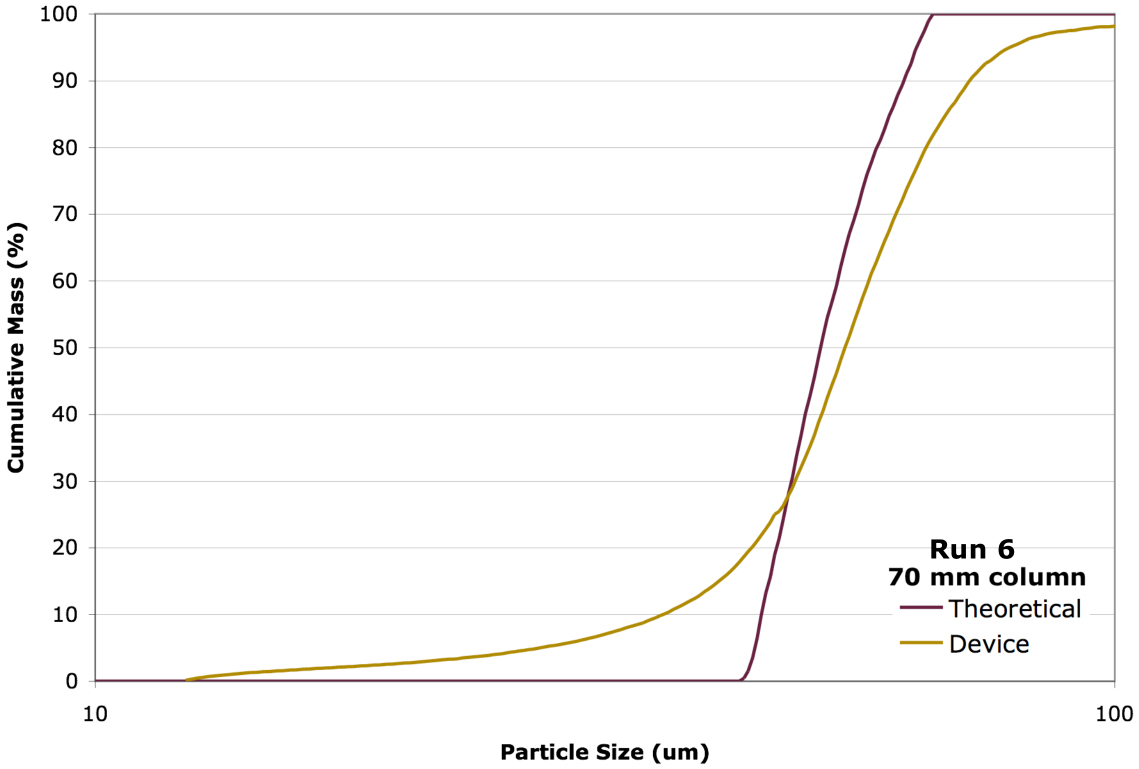
Figure B.2. Run 2 comparison of particle size distributions retained in each column versus uniform flow.

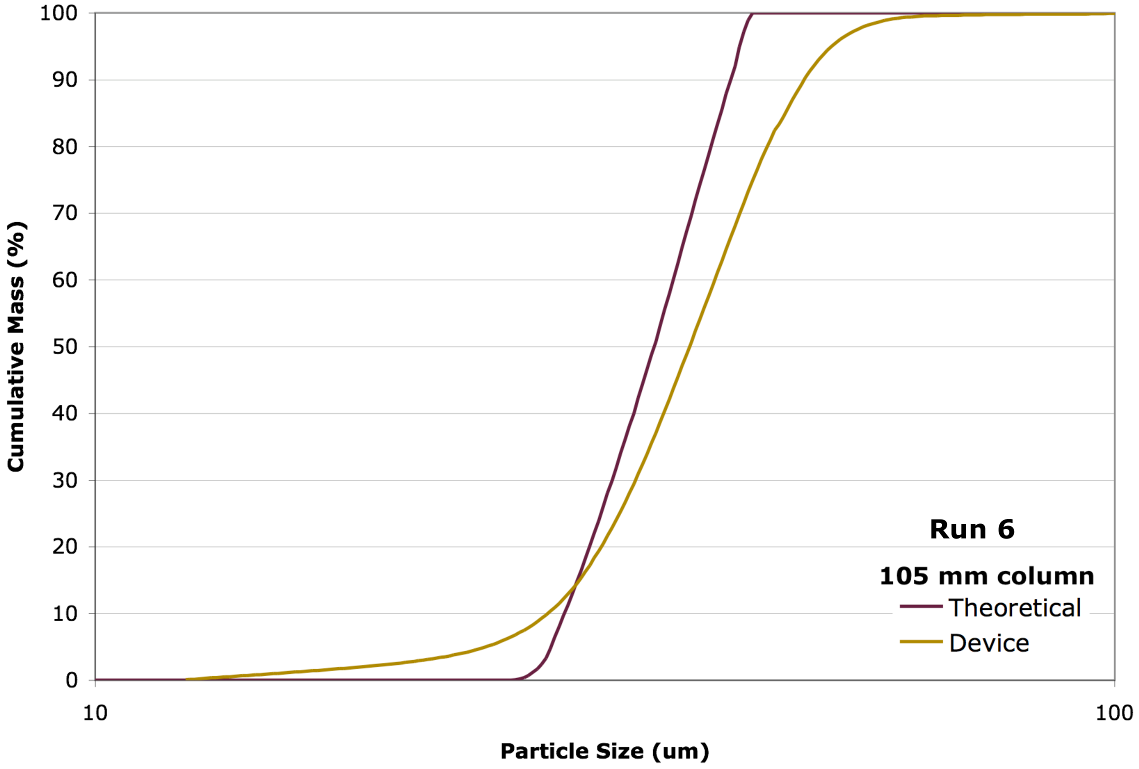


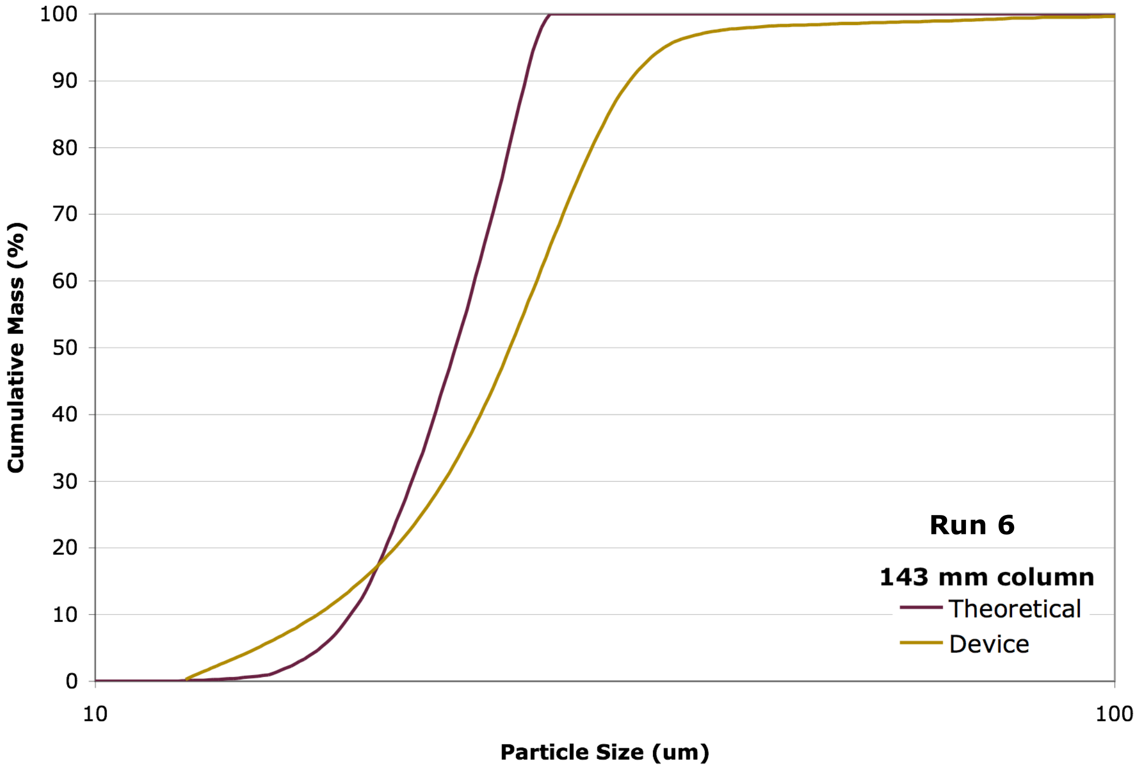
100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10
100
1000
Particle Size (um)
Run 6
34 mm column
Theoretical
Device



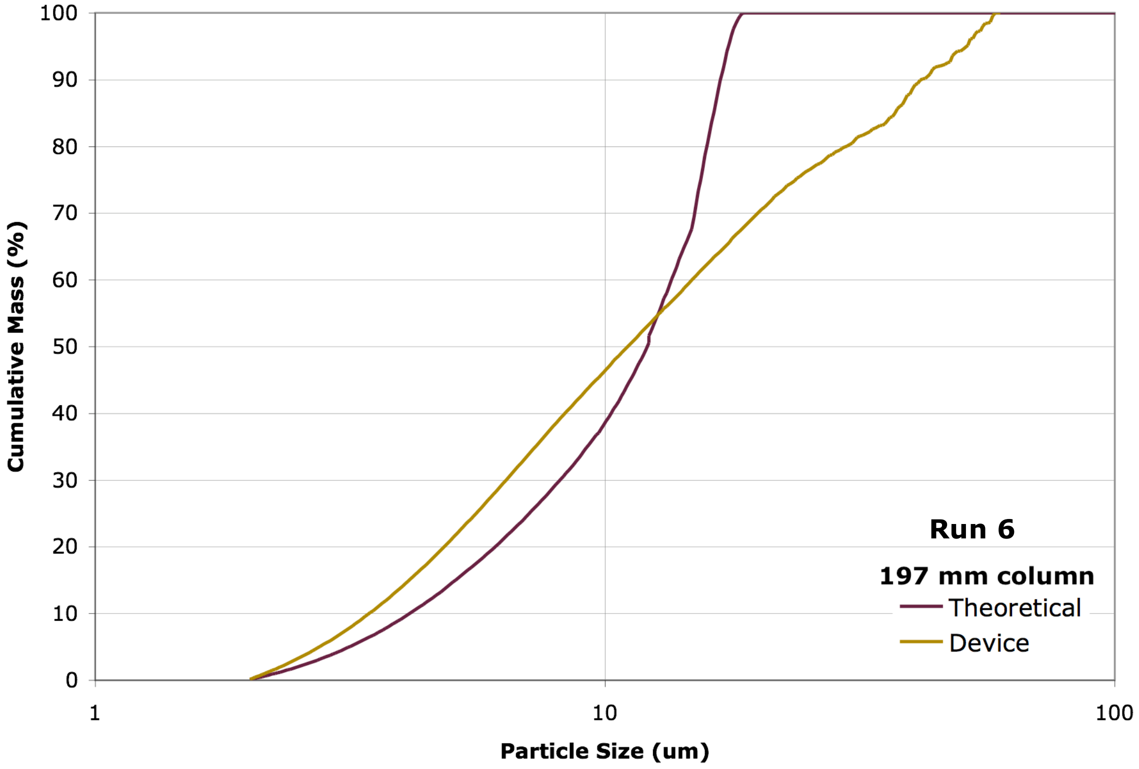
100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10
100
1000
Particle Size (um)
Run 6
49 mm column
Theoretical
Device


100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10
100
Particle Size (um)
Run 6
70 mm column
Theoretical
Device


100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10
100
Particle Size (um)
Run 6
105 mm column
Theoretical
Device



Cumulative Mass (%)
0
10
20
30
40
50
60
70
80
90
100
10
100
Particle Size (um)
Run 6
143 mm column
Theoretical
Device



Cumulative Mass (%)
0
10
20
30
40
50
60
70
80
90
100
1
10
100
Particle Size (um)
Run 6
197 mm column
Theoretical
Device

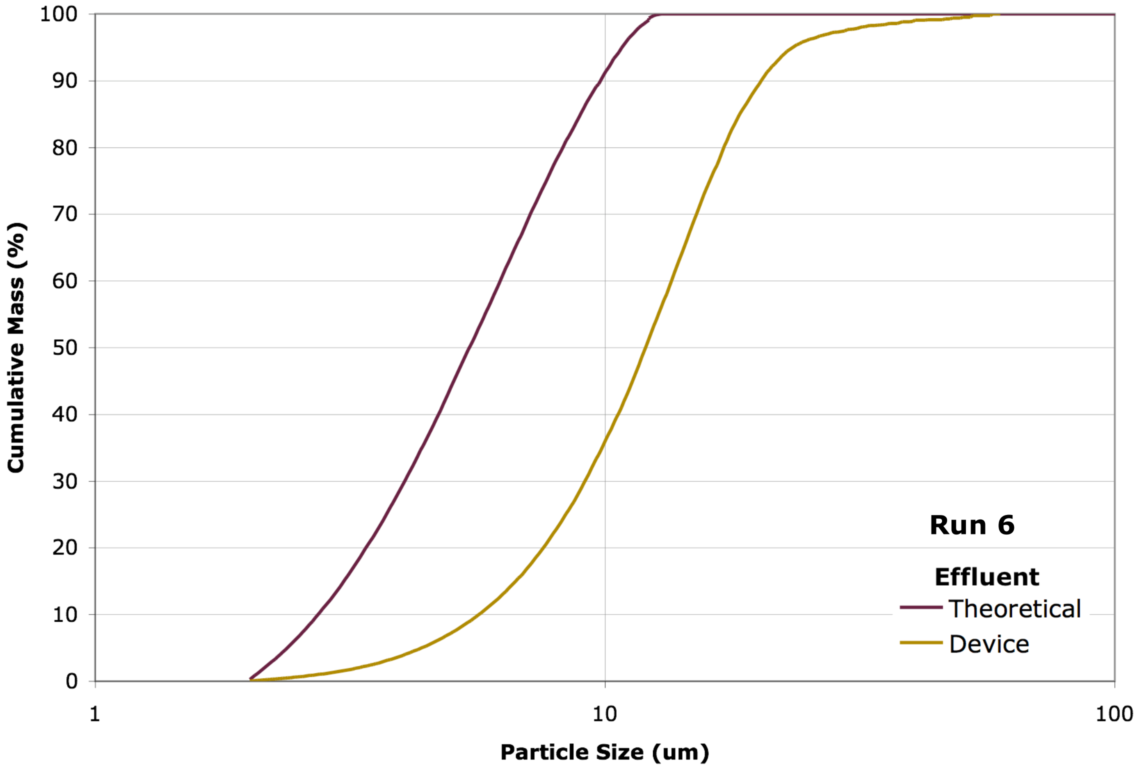
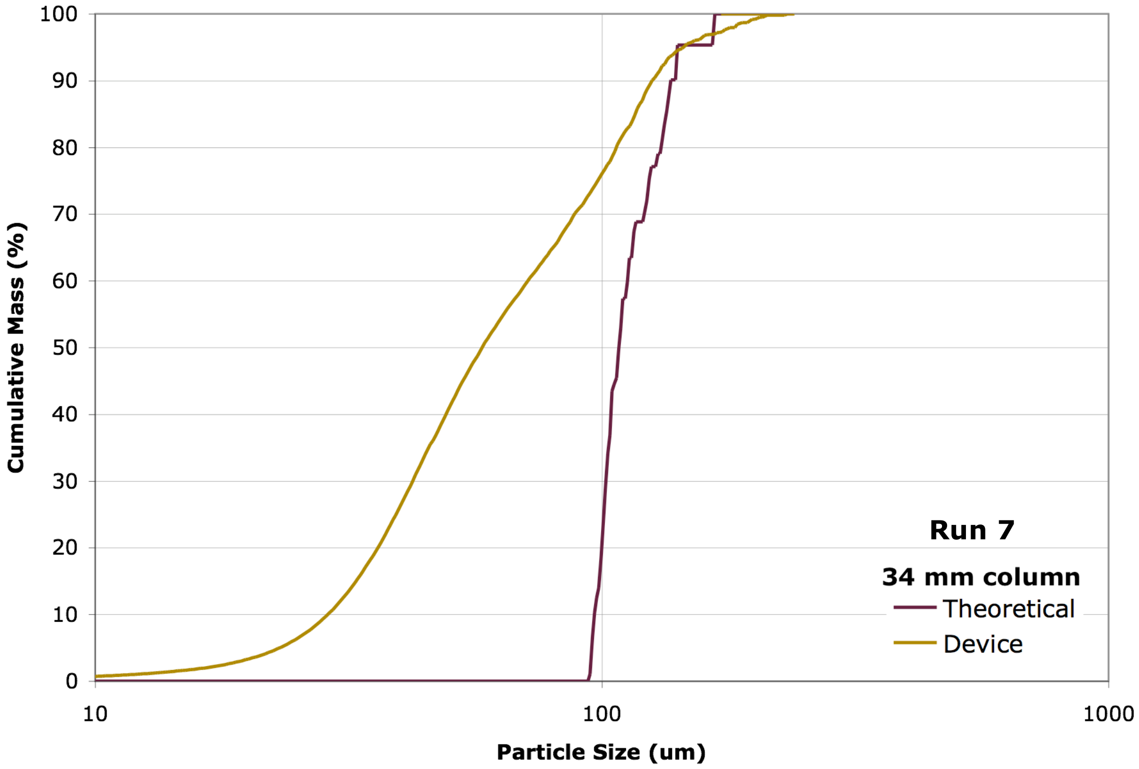
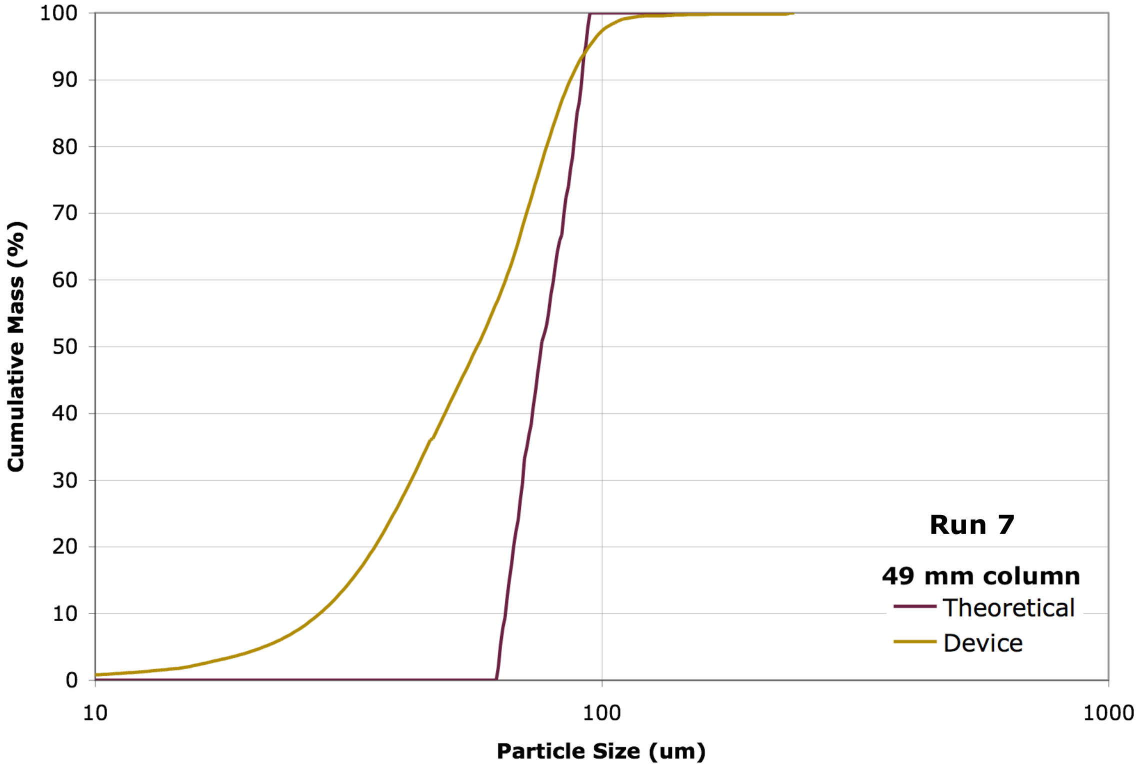
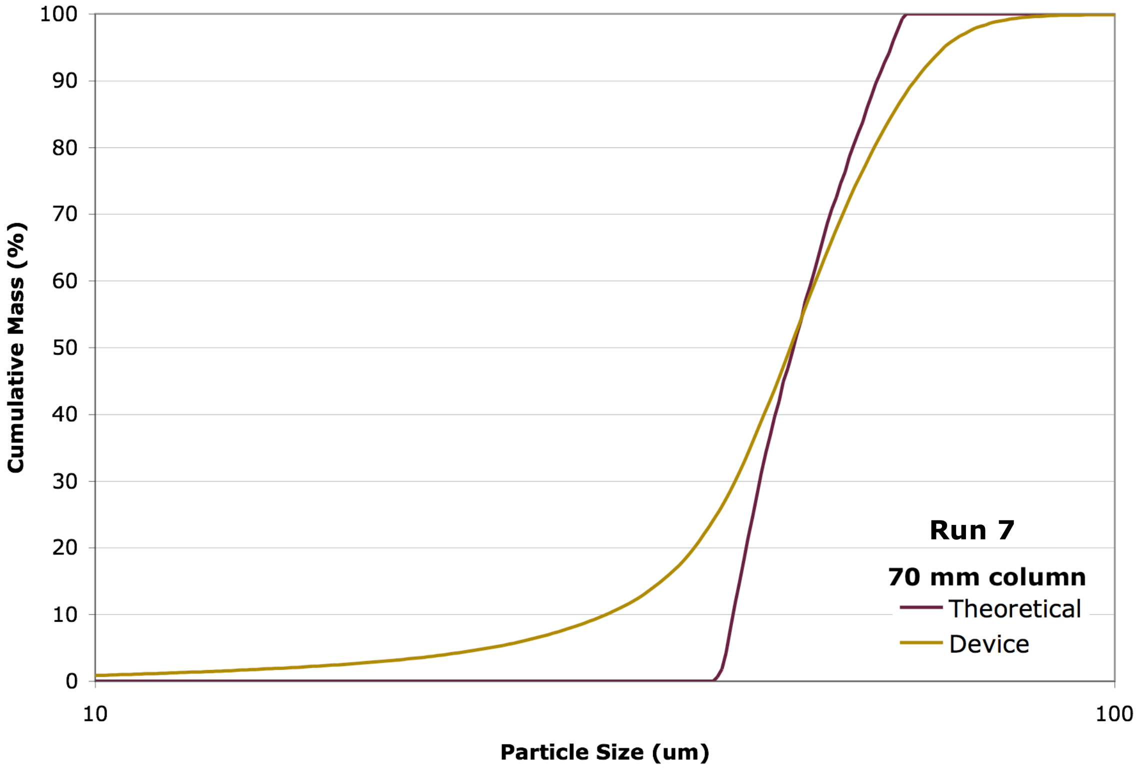
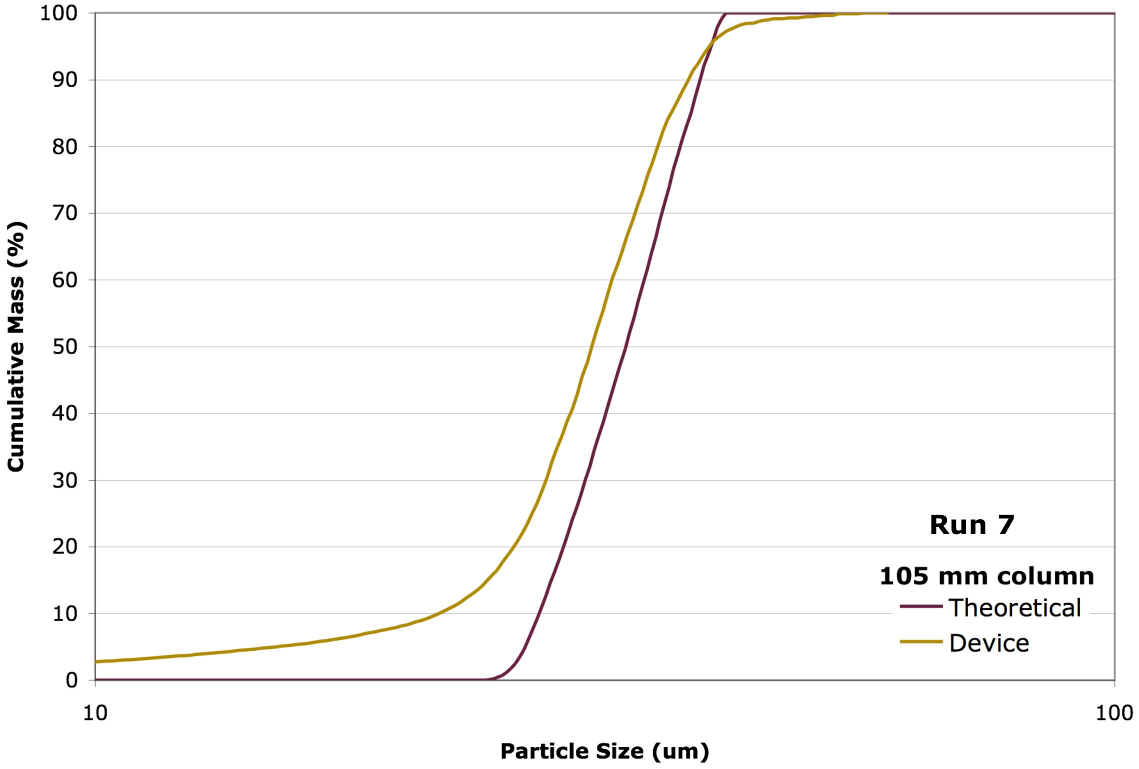


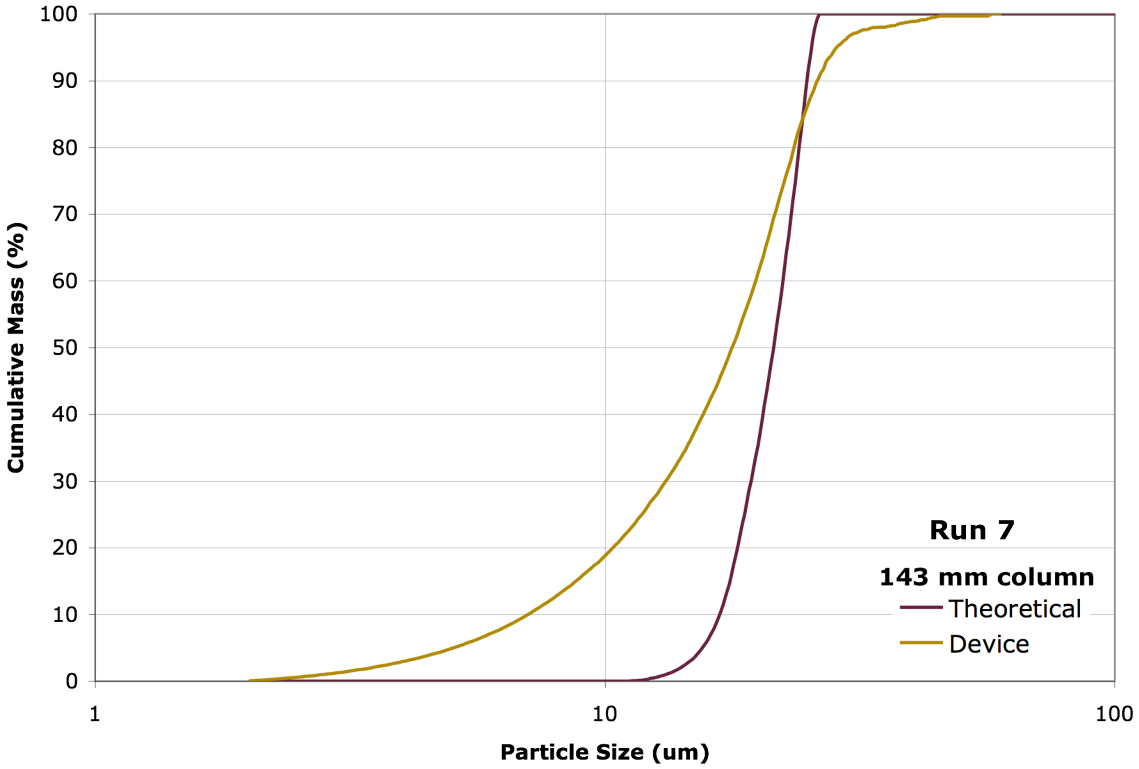
Figure B.3. Run 6 comparison of particle size distributions retained in each column versus uniform flow.


Cumulative Mass (%)
100
90
80
70
60
50
40
30
20
10
0
10
100
1000
Particle Size (um)
Run 7
34 mm column
Theoretical
Device

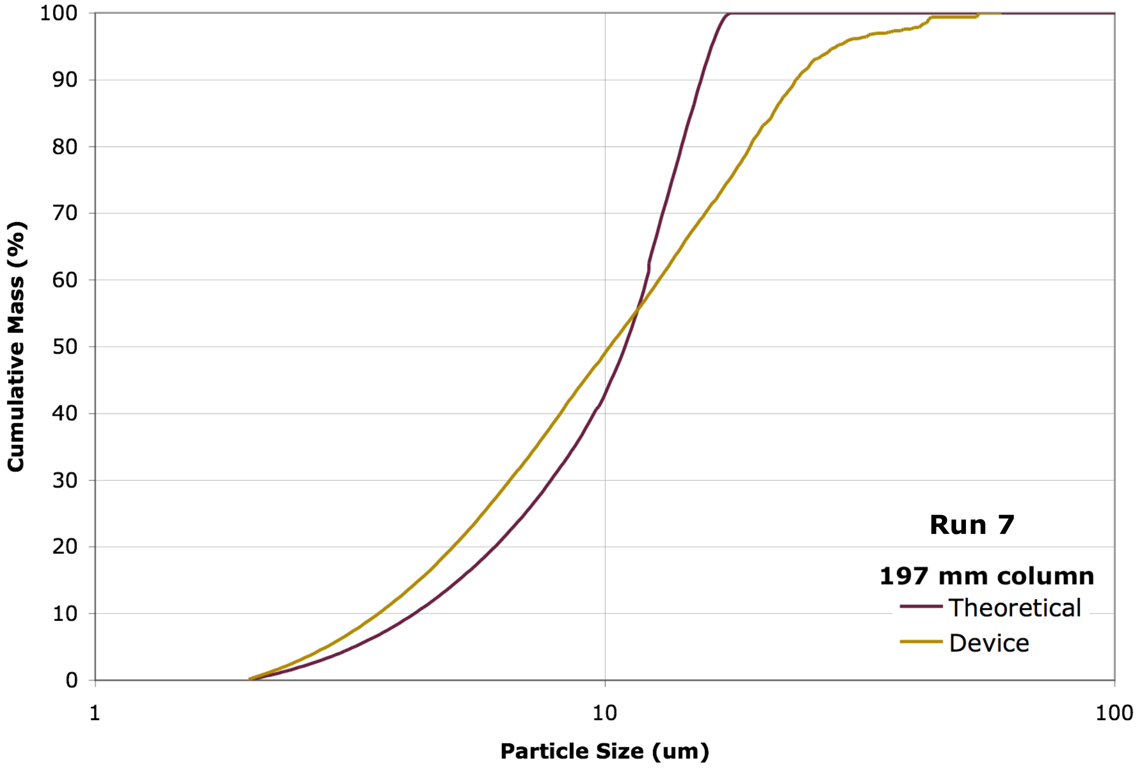

Cumulative Mass (%)
100
90
80
70
60
50
40
30
20
10
0
10
100
1000
Particle Size (um)
Run 7
49 mm column
Theoretical
Device


100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10
100
Particle Size (um)
Run 7
70 mm column
Theoretical
Device


100
90
80
70
60
50
40
30
20
10
0
Cumulative Mass (%)
10
100
Particle Size (um)
Run 7
105 mm column
Theoretical
Device



Cumulative Mass (%)
100
90
80
70
60
50
40
30
20
10
0
1
10
100
Particle Size (um)
Run 7
143 mm column
Theoretical
Device



Cumulative Mass (%)
100
90
80
70
60
50
40
30
20
10
0
1
10
100
Particle Size (um)
Run 7
197 mm column
Theoretical
Device

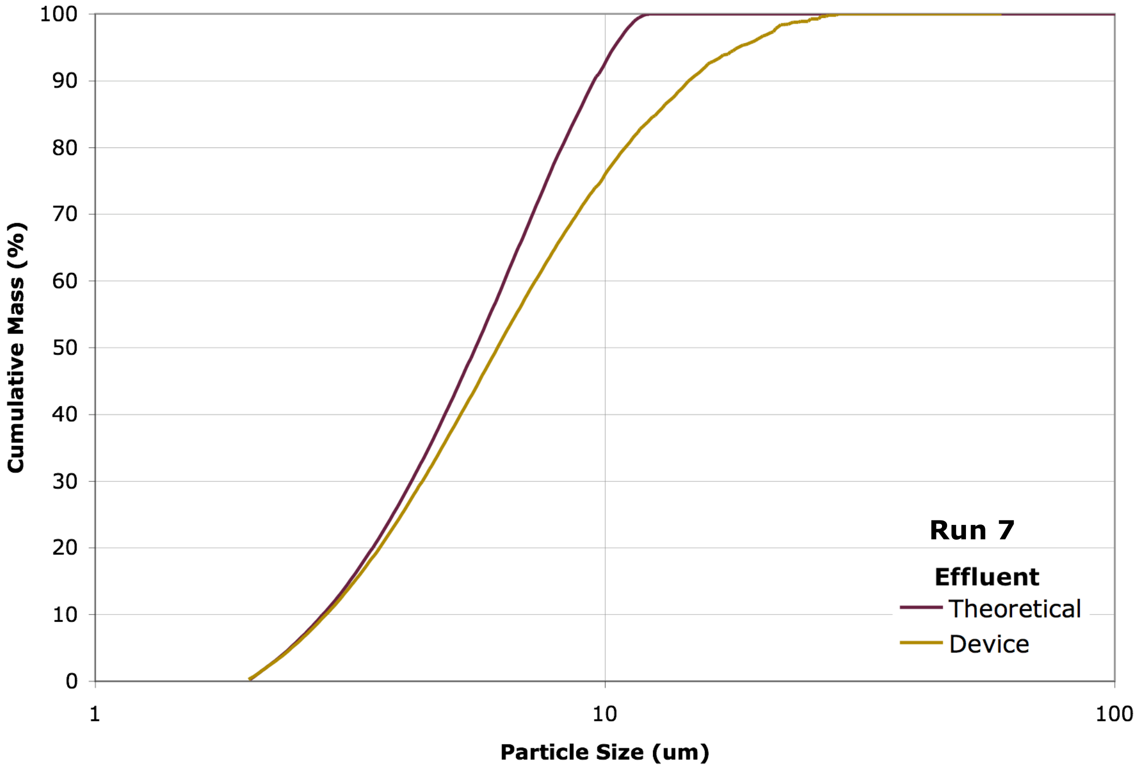
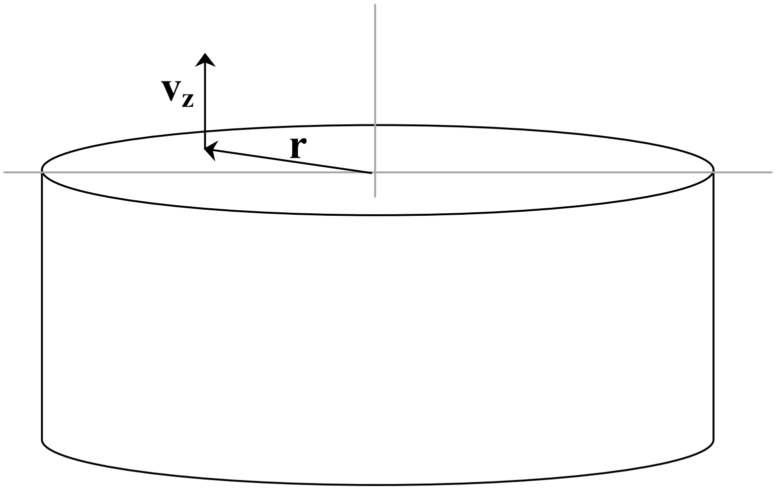


Figure B.4. Run 7 comparison of particle size distributions retained in each column versus uniform flow.

Appendix C. Derivation for Laminar Flow Profile through Cylinder

Adapted from Munson et al. 2006



- **Assumptions:**
  - Flow is parallel to walls
    $v_r = 0$, $v_\theta = 0$
  - From Continuity
    $\frac{\partial v_z}{\partial z} = 0$
  - Gravity only acts in horizontal direction
    $g_r = 0$, $g_q = 0$, $g_z = g$

- **Simplified Navier-Stokes Equations**

$$0 = -\frac{\partial p}{\partial r} \quad \text{Equation C.1}$$

$$0 = -\frac{1}{r} * \frac{\partial p}{\partial \theta} \quad \text{Equation C.2}$$

$$0 = -\frac{\partial p}{\partial z} + \rho g + \mu\left[\frac{1}{r} * \frac{\partial}{\partial r}\left(r * \frac{\partial v_z}{\partial r}\right)\right] \quad \text{Equation C.3}$$

- **Solutions**
  - Integrating Equations C.1 and C.2

$$p = f_1(z) \quad \text{Equation C.4}$$

  - Solve for Equation C.3

$$\left[\frac{1}{r} * \frac{\partial}{\partial r}\left(r * \frac{\partial v_z}{\partial r}\right)\right] = \frac{1}{\mu} * \frac{\partial p}{\partial z} - \frac{\rho g}{\mu}$$

- Integrate with respect to r

$$r\frac{\partial v_z}{\partial r}=\frac{1}{2\mu}\left(\frac{\partial p}{\partial z}\right)r^2-\frac{\rho g}{2\mu}*r^2+C_1$$

- Integrate again with respect to r

$$v_z=\frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)r^2-\frac{\rho g}{2\mu}*r^2+C_1\ln(r)+C_2$$

- C_1 = 0 because z should be finite at r = 0, v_z = 0 at r=R

$$0=\frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)R^2-\frac{\rho g}{4\mu}*R^2+C_2$$

$$C_2=R^2\left[\frac{\rho g}{4\mu}-\frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)\right]$$

- Velocity distribution becomes:

$$v_z=\frac{1}{4\mu}\left(\frac{\partial p}{dz}\right)r^2-\frac{\rho g}{4\mu}*r^2+R^2*\frac{\rho g}{4\mu}-R^2*\frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)$$

$$v_z=\frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)\left(r^2-R^2\right)-\frac{\rho g}{4\mu}\left(r^2-R^2\right)$$

Equation C.5

- Find relationship between Q and pressure gradient dA = (2πr)dr for ring

$$dQ=v_z(2\pi r)dr$$

$$Q=2\pi\int_0^R v_z*r*dr$$

- Solve for Q

$$Q=2\pi\int_0^R\left[\frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)\left(r^2-R^2\right)*r-\frac{\rho g}{4\mu}\left(r^2-R^2\right)*r\right]dr$$

$$Q=-2\pi\left[\frac{1}{4\mu}\left(\frac{\partial p}{\partial z}\right)-\frac{\rho g}{4\mu}\right]*\frac{R^4}{4}$$

$$\boxed{Q=\frac{-\pi}{8\mu}*\frac{\partial p}{\partial z}*R^4+\frac{\pi\rho g}{8\mu}*R^4}$$

Equation C.6

- Δp occurs over a length l

$$\frac{\Delta p}{l}=-\frac{\partial p}{\partial z}$$

- Therefore

$$\boxed{Q = \frac{\pi R^4}{8\mu}\left(\frac{\Delta p}{l} + \rho g\right)}$$ Equation C.7

- Rearranging Equation C.7

$$\left(\frac{\Delta p}{\mu l} + \frac{\rho g}{\mu}\right) = \frac{8Q}{\pi R^4}$$ Equation C.8

- Rearranging and simplifying Equation C.5

$$v_z = \frac{1}{4\mu}\left(\frac{\Delta p}{l} + \rho g\right)\left(R^2 - r^2\right)$$ Equation C.9

- Combining Equation C.8 and Equation C.9

$$\boxed{v_z = \frac{2Q}{\pi R^4}\left(\frac{\Delta p}{l} + \rho g\right)\left(R^2 - r^2\right)}$$ Equation C.10

Appendix D: Dimensions for Modified Elutriation Device Columns

The modified elutriation device consists of three columns with inner diameters of 2.47-in. (63 mm), 3.9-in (99 mm), and 6.0-in. (152 mm). The three columns are connected by 0.25-in. (6.3 mm) inner-diameter vinyl tubing. The following section shows the dimensions of the device.

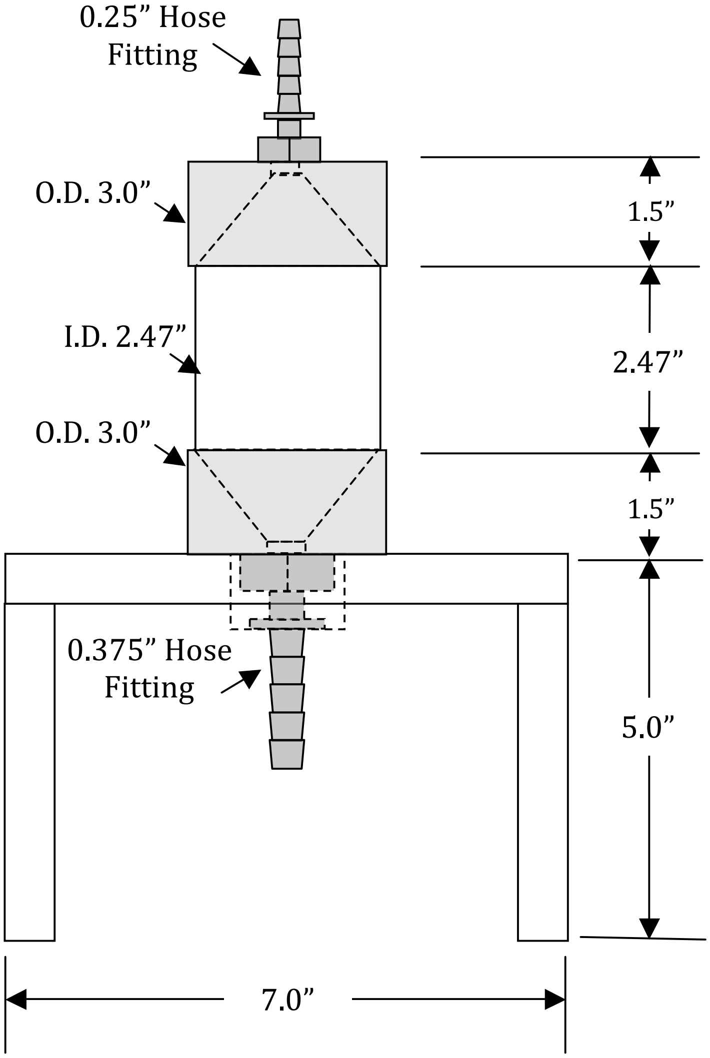


Figure D.1. Dimensions of 2.47-in (63 mm) column

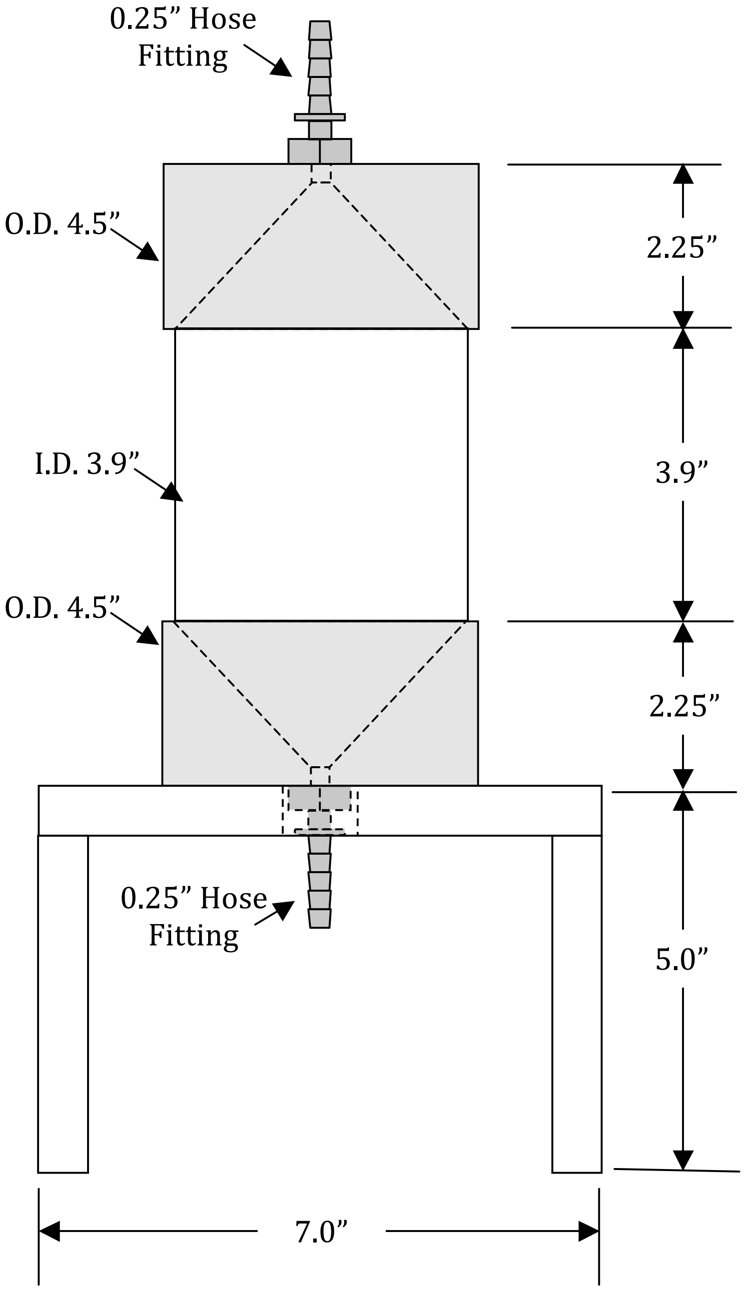


Figure D.2. Dimensions for 3.9-in. (99 mm) column.

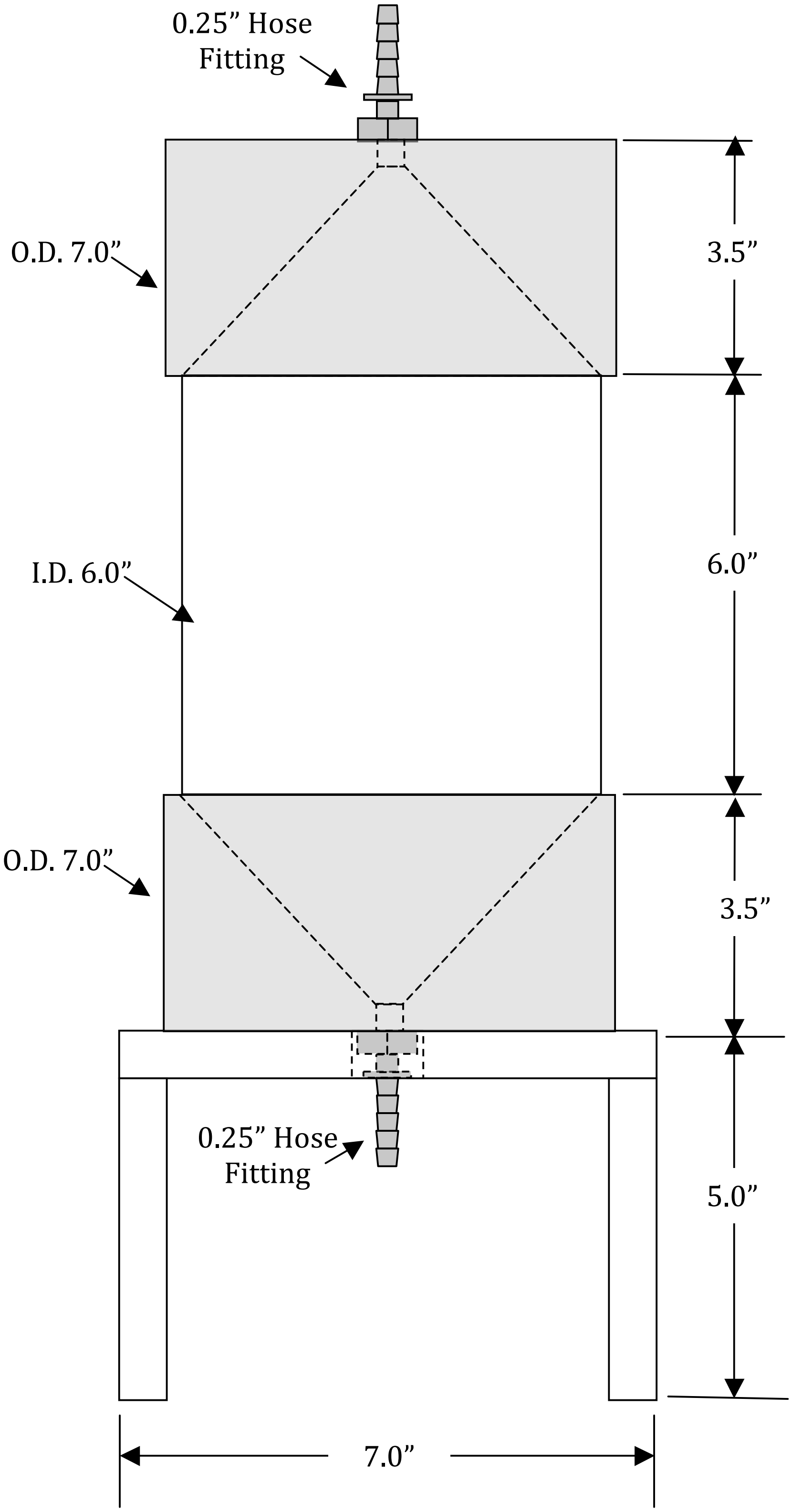


Figure D.3. Dimensions for 6.0-in. (152 mm) column.

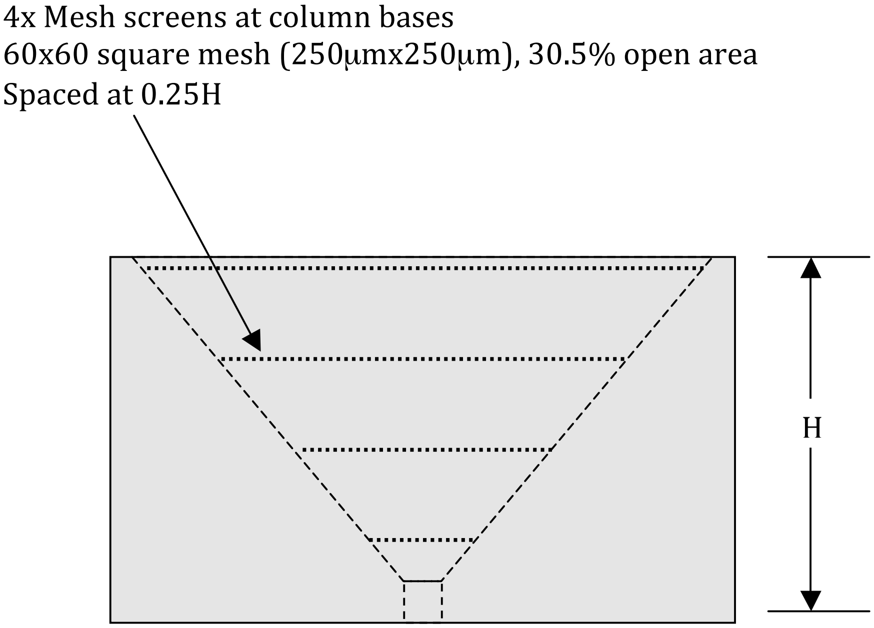


Figure D.4. Dimensions for mesh screens at column bottoms.

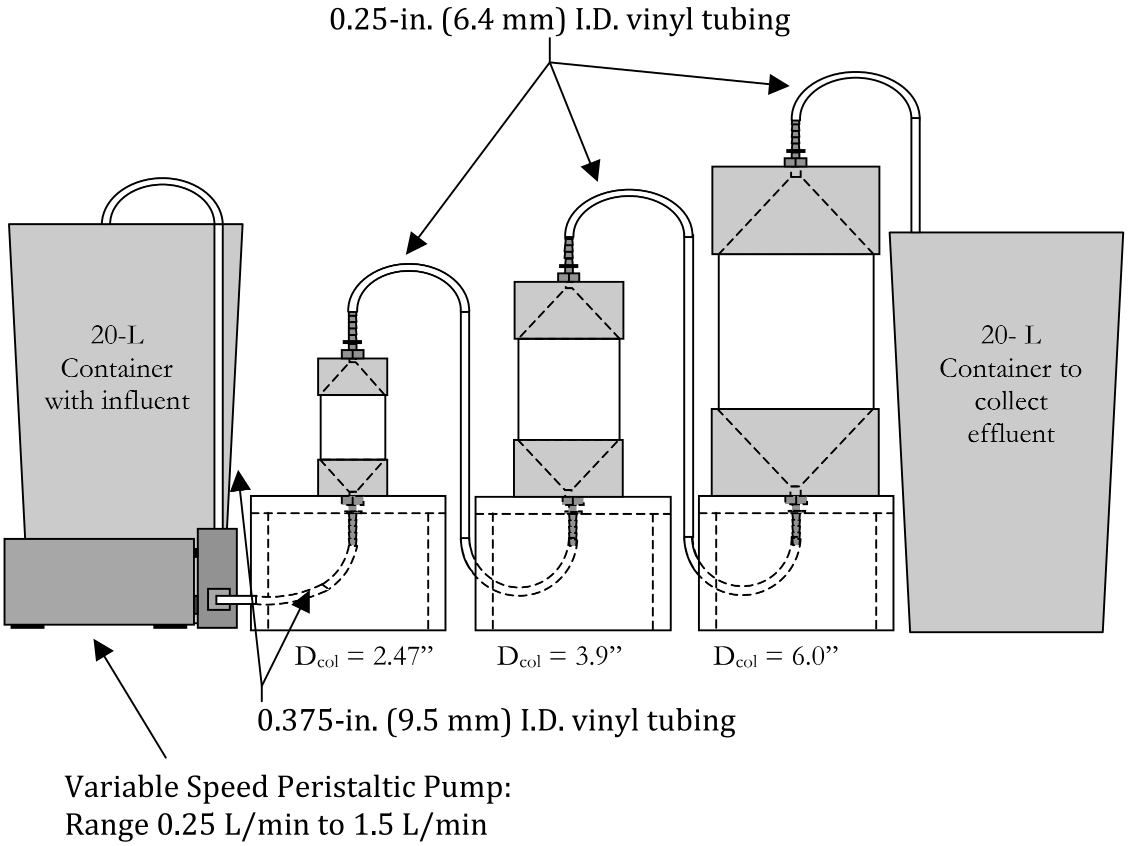


Figure D.5. Additional dimensions for Modified Elutriation Device.

Appendix E: Procedure for Testing Modified Elutriation Device

Operation for One Flow Rate*:*

1) Connect the 2.47-in. (62.7 mm), 3.9-in. (99.1 mm), and 6.0-in. (152 mm) columns with the 0.25-in. (6.4 mm) tubing as shown in Section A of Figure E.1.
2) Connect the 0.375-in. (9.5 mm) tube from the pump to the bottom of the 2.47-in (62.7 mm) column as shown in Section B of Figure E.1.
3) Fill each column completely with tap water.
4) Place 10-L of stormwater sample in a 20-L plastic bucket. Continuously mix with a paddle mixer.
5) Submerge the inlet tube in the influent bucket and turn on the pump to 0.5 L/min. Collect effluent in a clean 20-L bucket.

   Note: Keep the sample well mixed throughout the experiment. Also, run the inlet tube along the sides and the corners to ensure all particles enter the system.

6) When the entire stormwater sample is pumped from the bucket, pour 5 liters of clean tap water into the bucket.
7) Once all 5-L of clean tap water is pumped from the bucket, turn the pump off.
8) Collect the entire mass of sediment from each of the columns and the effluent (see below).

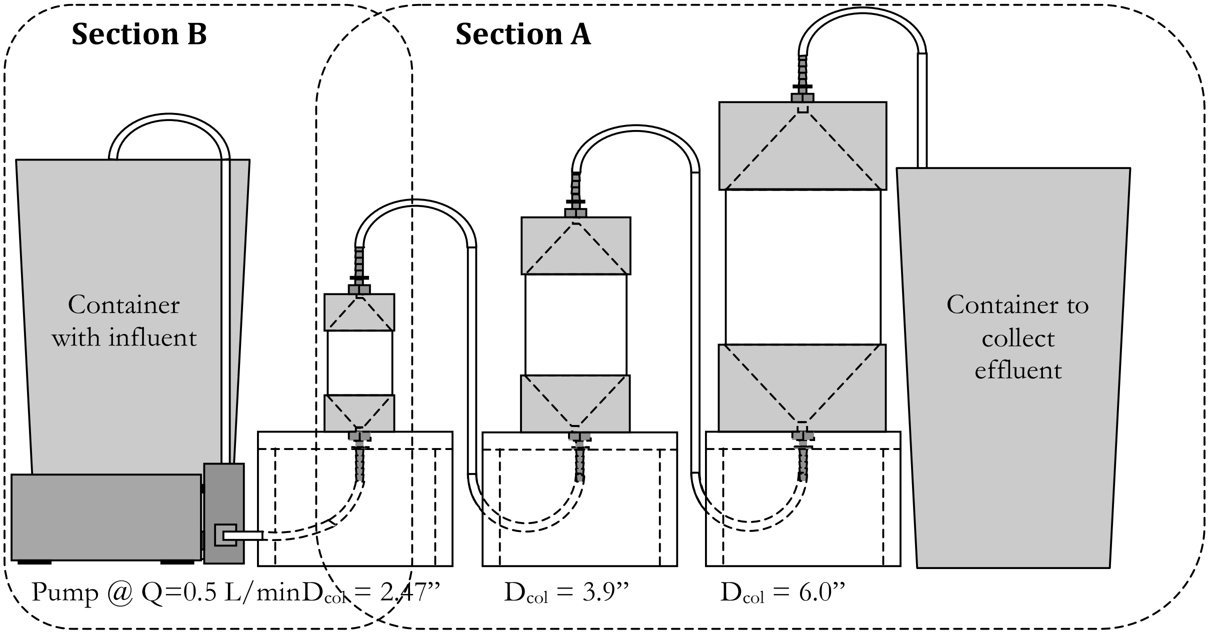


Figure E.1. Operation of Modified Elutriation Device with single flow rate.

Operation for Two Flow Rates:

1) Connect the 2.47-in. (62.7 mm) and 3.9-in. (99.1 mm) columns together with the 0.25-in. (6.4 mm) tubing as shown in Section A of Figure E.2.
2) Connect the 0.375-in. (9.5 mm) tube from the pump to the bottom of the 2.47-in (62.7 mm) column as shown in Section B of Figure E.2.
3) Fill the two columns completely with tap water.
4) Place 10-L of stormwater sample in a 20-L plastic bucket. Continuously mix with a paddle mixer.
5) Submerge the inlet tube in the influent bucket and turn on the pump to 1.5 L/min. Collect the effluent in a clean 20-L bucket.

   Note: Keep the sample well mixed throughout the experiment. Also, run the inlet tube along the sides and the corners to ensure all particles enter the system.

6) When the entire stormwater sample is pumped from the bucket, pour 5 liters of clean tap water into the bucket.
7) Once all 5-L of clean tap water is pumped from the bucket, turn the pump off.
8) Collect the entire mass from the 2.47-in. (62.7 mm) and 3.9-in. (99.1 mm) columns (see below for procedure).
9) Once the mass from the columns is collected, connect the 2.47-in (62.7 mm), 3.9-in. (99.1 mm), and 6.0-in. (152 mm) columns together with the 0.25-in. (6.4 mm) tubing as shown in Section C of Figure E.2.
10) Connect the 0.375-in. (9.5 mm) tube from the pump to the bottom of the 2.47-in (62.7 mm) column as shown in Section D of Figure E.1.
11) Fill the two columns completely with tap water.
12) Move the 15-L of effluent collected from steps 1-7 to the influent end of the new setup, as shown in Figure E.2. Continuously mix with a paddle mixer.
13) Submerge the inlet tube in the bucket with the 15-L collected in the previous run. Turn on the pump to 0.25 L/min. Collect the effluent in another clean 20-L bucket.

    Note: Keep the sample well mixed throughout the experiment. Also, run the inlet tube along the sides and the corners to ensure all particles enter the system.

14) When the entire 15-L sample is pumped from the bucket, pour 5 liters of clean tap water into the bucket.
15) Once all 5-L of clean tap water is pumped from the bucket, turn the pump off.
16) Collect the entire mass of sediment from each of the columns and the effluent (see below).

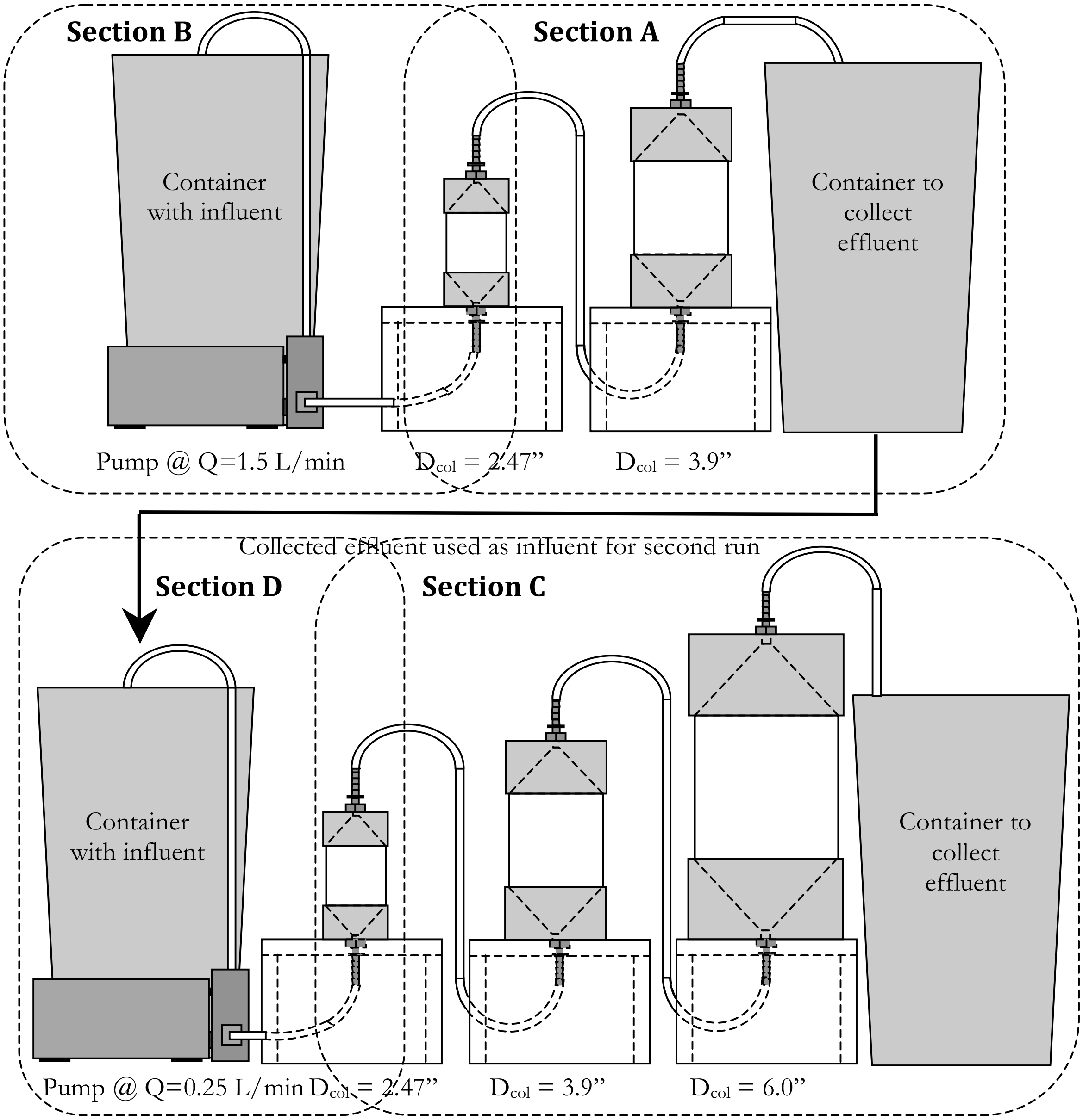


Figure E.2. Operation of Modified Elutriation Device with two flow rates.

Sediment collection for experimental runs including two smallest columns:

1) Start by removing the 0.25-in. (6.4 mm) tube from the top of the 2.47-in. (62.7 mm) column. The tube should still be connected to the 3.9-in. (99.1 mm) column.
2) Lower the 0.25-in. (6.4 mm) tube below the 3.9-in. (99.1 mm) column, and collect water and particles in a 2-L container. Make sure all sediment is collected by washing the sides of the column and the screens using a stream of water.

3) For the 2.47-in. (62.7 mm) column, place the 0.375-in. (9.5 mm) tube connected to the pump in a 1-L clean container.
4) Switch the pump to Reverse and collect the water from the column. Make sure all sediment is collected by washing the sides of the column and the screens using a stream of water.

Sediment collection for experimental runs including three columns:

1) Start by removing the 0.25-in. (6.4 mm) tube from the top of the 3.9-in. (99.1 mm) column. The tube should still be connected to the 6.0-in. (152 mm) column.
2) Lower the 0.25-in. (6.4 mm) tube below the 6.0-in. (152 mm) column, and collect water and particles in a 5-L container. Make sure all sediment is collected by washing the sides of the column and the screens using a stream of water.
3) Once the 6.0-in (152 mm) column is empty, repeat steps 1 and 2 for the 3.9-in. (99.1 mm) column. Use a 2-L container to collect all water and sediment from the column.
4) For the 2.47-in. (62.7 mm) column, place the 0.375-in. (9.5 mm) tube connected to the pump in a 1-L clean container.
5) Switch the pump to Reverse and collect the water from the column. Make sure all sediment is collected by washing the sides of the column and the screens using a stream of water.

Collecting effluent samples:

1) Determine the total mass of the effluent by determining the mass of the bucket and water/sediment mixture. Measure the mass of the empty bucket. Subtract the mass of the bucket from the mass of the bucket/water combination.
2) Determine the volume of the water/sediment mixture by dividing the mass of the water by the density of the water (depends on temperature).
3) Thoroughly mix the effluent by switching back and forth between two clean buckets six times.
4) Take a 200-mL sample of the effluent using the 100-mL pipette. Collect a total of three samples.

Analyzing Mass of Samples:

1) Set glass fiber filters with 0.45 μm nominal pore size.

2) Measure and record the mass of ceramic crucibles + filters to the 0.0000 gram.

3) Filter the water/sediment sample collected from each column through individual filters.

4) Filter the 200-mL effluent samples through individual filters.

5) Dry samples for 1 hour in an oven at 100°C

6) Remove samples from oven and let cool for 15 minutes. Measure and record mass of ceramic crucibles + filters + sediment to the 0.0000 gram.

7) For each of the columns, determine the final mass by subtracting the mass of the crucible/filter from the mass of the crucible/filter/sediment.

8) Determine the mass of the effluent.

   A. Determine the mass of the particles retained in each 200-mL sample.

   B. Calculate the concentration of the effluent by dividing the mass of the sample by the volume of the sample (units in mg/L).

   C. Calculate the total mass in the effluent by multiplying the concentration of the effluent by the volume of the effluent.

Appendix F: Program for Estimating Performance of Elutriation Device

F.1. Written Description of Program

Description: A program was created in Microsoft Excel using Visual Basic for Applications. The program estimates the performance of a three column elutriation device based on the initial particle size distribution.

Program Inputs:

- Total particle mass (m_{total})
- Particle density
- Influent particle size distribution
- Column diameter (d_{column})
- Column length (l_{column})
- Device flow rate (Q_{device})
- Volume of water/sediment mixture pumped through device ($V_{sediment}$)
- Volume of clean water pumped through device (V_{clean})
- Temperature (to determine density and viscosity of water)

Program Assumptions:

1) The water/sediment mixture is well mixed so the concentration of each particle size is the same throughout the suspension.
2) When particles enter the device, they become evenly distributed across the cross-sectional area of the columns.
3) All particles in the distribution have the same density.
4) The particle size distribution of particles entering the system (measured by the Multisizer III coulter counter) is accurate.

Program Details for Single Column:

1) For the column, assume a laminar flow profile.
2) At various points along the cross-section of the column, calculate the upward velocity (v_{up}) using theory described in Appendix A and C. Also calculate the

differential area ($\Delta A/A_{total}$) for each point in the cross section. An example of the calculated values for the 1.5-inch column is shown in Table F.1.

Table F.1. Example of calculated v_{up} and $\Delta A/A$ values for 1.5-inch column

r_{upper} (m)	v_{up} (m/s)	ΔA (m^2)	ΔA_{diff}	$\Delta A_{diff}/A_{tot}$
0.00E+00	0.01866	0.00000	0.0000	0.0000
1.35E-03	0.01857	0.00001	0.00001	0.0050
1.91E-03	0.01847	0.00001	0.00001	0.0050
2.33E-03	0.01838	0.00002	0.00001	0.0050
2.69E-03	0.01829	0.00002	0.00001	0.0050
3.01E-03	0.01820	0.00003	0.00001	0.0050
3.30E-03	0.01810	0.00003	0.00001	0.0050

3) For each particle diameter bin generated by the coulter counter, calculate a settling velocity for the corresponding particle size. The settling velocity is calculated using the Ferguson and Church (2004) equation.
4) For each individual particle size and each differential upward velocity across the cross-section of the column, circulate an upward velocity ($\Delta v = v_{up} - v_{particle}$).
5) If the settling velocity of a particle is greater than the upward velocity in the column ($\Delta v < 0$), then 100 percent of the particles in that size range will be retained in the column.
6) If the settling velocity of a particle is less than the upward velocity in the column ($\Delta v > 0$), calculate the time required for particles to get flushed through the system.
   A. Calculate the amount of time required for the first particle of a specified size that enters the column to get flushed through the column by comparing the differential upward velocity to the column length ($t_{first} = l_{column}/\Delta v$)

B. Calculate the amount of time required for the final particle of a specific size to pass through the column by comparing the volume of the influent to the flow rate ($t_{final} = t_{first} + V_{sediment}/Q_{device}$).

C. Calculate the total operation time for the device by comparing the volume of the water/sediment mixture and the clean water to the device flow rate ($t_{total} = [V_{sediment} + V_{clean}]/Q_{device}$).

7) For each individual particle size and differential column area, calculate a differential mass coefficient for the combination ($\Delta m = \Delta m_{size}*[\Delta A_{diff}/A_{tot}]*m_{total}$).

8) Determine the amount of mass retained in the column given different conditions.

   A. If the amount of time required for a particle to get flushed through the column is less than the total amount of time ($t_{final} < t_{total}$), then none of those particles are retained in the column. ($\Delta m_{column} = 0$, $\Delta m_{effluent} = \Delta m$)

   B. If the amount of time required for a particle to get flushed through the column is greater than the total amount of time required, a more elaborate calculation must be used. The amount of mass retained in the column relates to the difference between the amount of time for the first particle to get flushed through the system and the total device operation. ($\Delta m_{effluent} = \Delta m*[t_{total}-t_{first}]/t_{total}$, $\Delta m_{column} = \Delta m - \Delta m_{effluent}$).

9) Steps 3 through 8 are repeated for each individual particle size and each differential slice of the column. As the program continues, terms for the total mass retained in the column and the total mass passed through the column to the effluent are calculated ($m_{column-total} = \Sigma\Delta m_{column}$, $m_{effluent-total} = \Sigma\Delta m_{effluent}$).

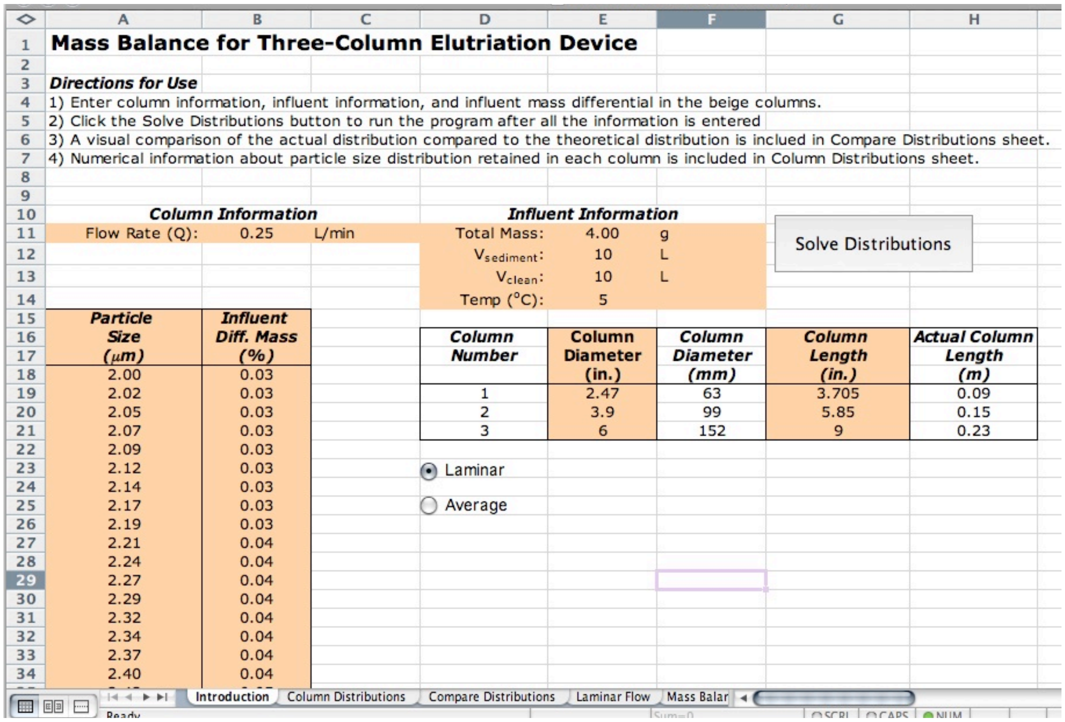
10) Once the program is complete, it provides the mass retained in the column and in the effluent. Additionally, the program provides a particle size distribution of particles retained in each column and in the effluent.

Program Details for Multiple Column Elutriation Device:

1) For an elutriation device that links columns with increasing diameter, the assumptions and the device inputs are the same as described above. The major difference is the diameter and length of all columns used in the device must be defined.
2) The equations and methods described in steps 1 through 9 above are the same for a multiple column elutriation device, but the equations apply to each individual column.
3) The program to determine the distribution for multiple column elutriation devices incorporates one major difference: as the initial particle size distribution passes through each column, the particle size distribution entering each column changes.
    a. The particles entering the first column will have a certain distribution. Some of the larger particles in the distribution will be retained in the column, so the particle size distribution exiting the first column and entering the second column will be finer than the influent particle size distribution.
    b. A major assumption is made in the program for multiple column elutriation devices. The amount of time required for a particle of a specific size to enter the subsequent columns is assumed to be the time it takes for the first particle to exit the system assuming a uniform flow profile ($t_{enter\text{-}column2} = l_{column1}/[v_{uniform}\text{-}v_{particle}]$). Note: This assumption may introduce slight error in the program because some particles will enter the subsequent columns more quickly than the equation states. Nonetheless, particles closer to the column edge will enter the subsequent columns more slowly than the equation states so the use of the uniform flow velocity is reasonable.
4) Once the program is complete, the program provides the mass retained in each column and in the effluent. Additionally, the program provides a particle size distribution of particles retained in each column and in the effluent.

F.2. Layout of Spreadsheets Used in Program

The spreadsheet program to estimate the performance of a three-column elutriation device utilizes four different worksheets. The first worksheet, the Introduction worksheet, is pictured in Figure F.1. The user directly inputs information about the columns, the influent distribution, and the device operation. Other worksheets include a worksheet that calculates the velocity at various points across the column cross section (Laminar Flow), a worksheet that calculates the mass of particles retained in each column (Mass Balance), and a worksheet that copies information about mass retained in each column (Column Distributions). The layout of the worksheets are pictured in Figure F.2., Figure F.3., and Figure F.4., respectively.



Mass Balance for Three-Column Elutriation Device

Directions for Use

1) Enter column information, influent information, and influent mass differential in the beige columns.
2) Click the Solve Distributions button to run the program after all the information is entered
3) A visual comparison of the actual distribution compared to the theoretical distribution is inclued in Compare Distributions sheet.
4) Numerical information about particle size distribution retained in each column is included in Column Distributions sheet.

Column Information

Flow Rate (Q): 0.25 L/min

Influent Information

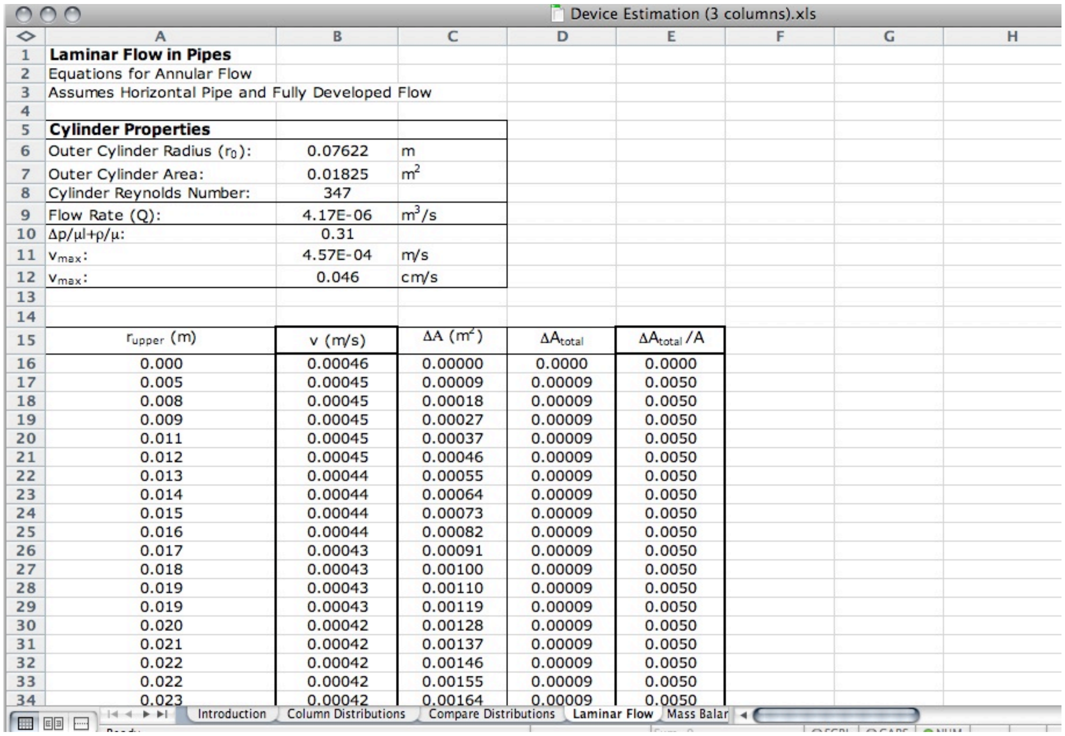
Total Mass: 4.00 g
$V_{sediment}$: 10 L
V_{clean}: 10 L
Temp (°C): 5

Particle Size (μm)	***Influent Diff. Mass (%)***
2.00	0.03
2.02	0.03
2.05	0.03
2.07	0.03
2.09	0.03
2.12	0.03
2.14	0.03
2.17	0.03
2.19	0.03
2.21	0.04
2.24	0.04
2.27	0.04
2.29	0.04
2.32	0.04
2.34	0.04
2.37	0.04
2.40	0.04

Column Number	**Column Diameter (in.)**	***Column Diameter (mm)***	***Column Length (in.)***	***Actual Column Length (m)***
1	2.47	63	3.705	0.09
2	3.9	99	5.85	0.15
3	6	152	9	0.23

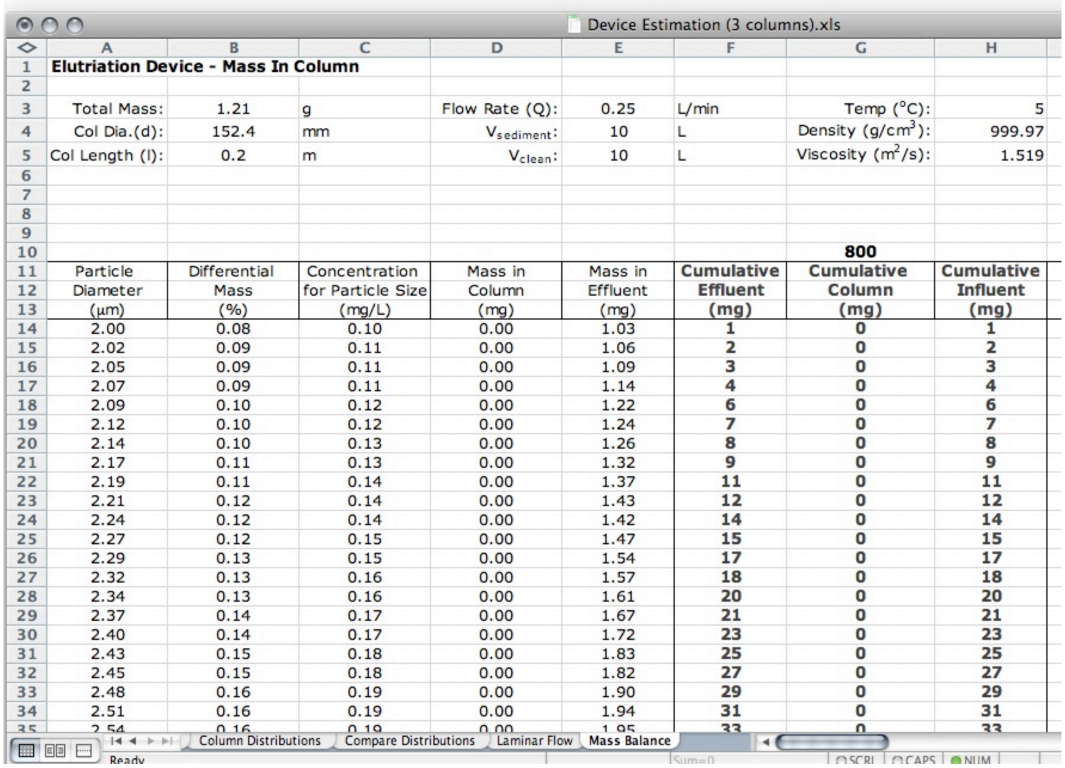
● Laminar
○ Average

Figure F.1. Introduction sheet for inputting information about elutriation device.



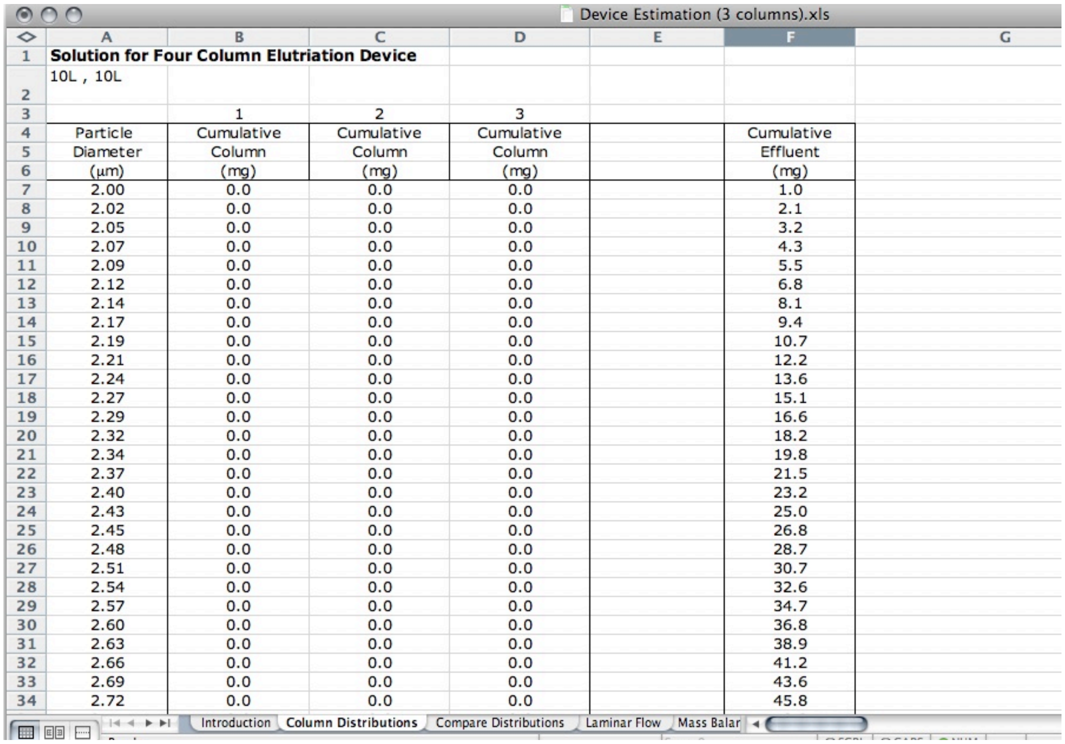
	A	B	C	D	E
1	**Laminar Flow in Pipes**				
2	Equations for Annular Flow				
3	Assumes Horizontal Pipe and Fully Developed Flow				
4					
5	**Cylinder Properties**				
6	Outer Cylinder Radius (r_0):	0.07622	m		
7	Outer Cylinder Area:	0.01825	m^2		
8	Cylinder Reynolds Number:	347			
9	Flow Rate (Q):	4.17E-06	m^3/s		
10	$\Delta p/\mu l+\rho/\mu$:	0.31			
11	v_{max}:	4.57E-04	m/s		
12	v_{max}:	0.046	cm/s		
13					
14					
15	r_{upper} (m)	v (m/s)	ΔA (m^2)	ΔA_{total}	$\Delta A_{total}/A$
16	0.000	0.00046	0.00000	0.0000	0.0000
17	0.005	0.00045	0.00009	0.00009	0.0050
18	0.008	0.00045	0.00018	0.00009	0.0050
19	0.009	0.00045	0.00027	0.00009	0.0050
20	0.011	0.00045	0.00037	0.00009	0.0050
21	0.012	0.00045	0.00046	0.00009	0.0050
22	0.013	0.00044	0.00055	0.00009	0.0050
23	0.014	0.00044	0.00064	0.00009	0.0050
24	0.015	0.00044	0.00073	0.00009	0.0050
25	0.016	0.00044	0.00082	0.00009	0.0050
26	0.017	0.00043	0.00091	0.00009	0.0050
27	0.018	0.00043	0.00100	0.00009	0.0050
28	0.019	0.00043	0.00110	0.00009	0.0050
29	0.019	0.00043	0.00119	0.00009	0.0050
30	0.020	0.00042	0.00128	0.00009	0.0050
31	0.021	0.00042	0.00137	0.00009	0.0050
32	0.022	0.00042	0.00146	0.00009	0.0050
33	0.022	0.00042	0.00155	0.00009	0.0050
34	0.023	0.00042	0.00164	0.00009	0.0050

Figure F.2. Laminar Flow sheet to determine upward velocity at points within column.



	A	B	C	D	E	F	G	H
1	**Elutriation Device - Mass In Column**							
2								
3	Total Mass:	1.21	g	Flow Rate (Q):	0.25	L/min	Temp (°C):	5
4	Col Dia.(d):	152.4	mm	$V_{sediment}$:	10	L	Density (g/cm^3):	999.97
5	Col Length (l):	0.2	m	V_{clean}:	10	L	Viscosity (m^2/s):	1.519
6								
7								
8								
9								
10							**800**	
11–13	Particle Diameter (µm)	Differential Mass (%)	Concentration for Particle Size (mg/L)	Mass in Column (mg)	Mass in Effluent (mg)	**Cumulative Effluent (mg)**	**Cumulative Column (mg)**	**Cumulative Influent (mg)**
14	2.00	0.08	0.10	0.00	1.03	**1**	**0**	**1**
15	2.02	0.09	0.11	0.00	1.06	**2**	**0**	**2**
16	2.05	0.09	0.11	0.00	1.09	**3**	**0**	**3**
17	2.07	0.09	0.11	0.00	1.14	**4**	**0**	**4**
18	2.09	0.10	0.12	0.00	1.22	**6**	**0**	**6**
19	2.12	0.10	0.12	0.00	1.24	**7**	**0**	**7**
20	2.14	0.10	0.13	0.00	1.26	**8**	**0**	**8**
21	2.17	0.11	0.13	0.00	1.32	**9**	**0**	**9**
22	2.19	0.11	0.14	0.00	1.37	**11**	**0**	**11**
23	2.21	0.12	0.14	0.00	1.43	**12**	**0**	**12**
24	2.24	0.12	0.14	0.00	1.42	**14**	**0**	**14**
25	2.27	0.12	0.15	0.00	1.47	**15**	**0**	**15**
26	2.29	0.13	0.15	0.00	1.54	**17**	**0**	**17**
27	2.32	0.13	0.16	0.00	1.57	**18**	**0**	**18**
28	2.34	0.13	0.16	0.00	1.61	**20**	**0**	**20**
29	2.37	0.14	0.17	0.00	1.67	**21**	**0**	**21**
30	2.40	0.14	0.17	0.00	1.72	**23**	**0**	**23**
31	2.43	0.15	0.18	0.00	1.83	**25**	**0**	**25**
32	2.45	0.15	0.18	0.00	1.82	**27**	**0**	**27**
33	2.48	0.16	0.19	0.00	1.90	**29**	**0**	**29**
34	2.51	0.16	0.19	0.00	1.94	**31**	**0**	**31**
35	2.54	0.16	0.19	0.00	1.95	**33**	**0**	**33**

Figure F.3. Mass Balance sheet to calculate particles retained in each column.



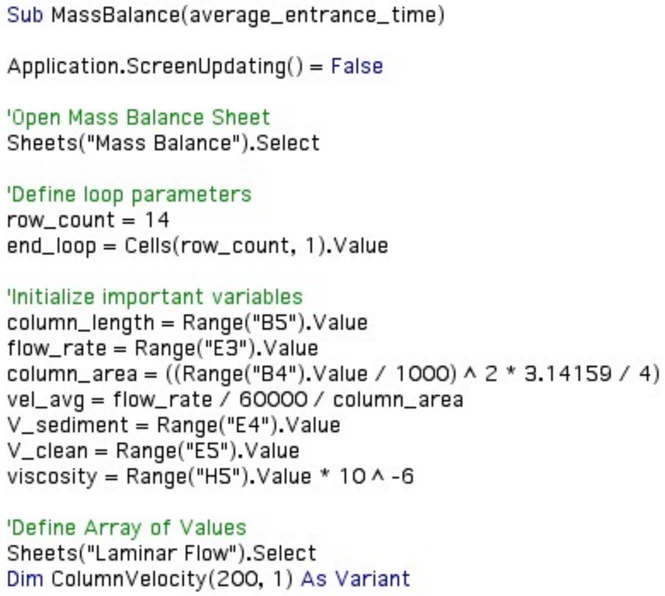
Device Estimation (3 columns).xls

	A	B	C	D	E	F	G
1	**Solution for Four Column Elutriation Device**						
2	10L , 10L						
3		1	2	3			
4	Particle	Cumulative	Cumulative	Cumulative		Cumulative	
5	Diameter	Column	Column	Column		Effluent	
6	(µm)	(mg)	(mg)	(mg)		(mg)	
7	2.00	0.0	0.0	0.0		1.0	
8	2.02	0.0	0.0	0.0		2.1	
9	2.05	0.0	0.0	0.0		3.2	
10	2.07	0.0	0.0	0.0		4.3	
11	2.09	0.0	0.0	0.0		5.5	
12	2.12	0.0	0.0	0.0		6.8	
13	2.14	0.0	0.0	0.0		8.1	
14	2.17	0.0	0.0	0.0		9.4	
15	2.19	0.0	0.0	0.0		10.7	
16	2.21	0.0	0.0	0.0		12.2	
17	2.24	0.0	0.0	0.0		13.6	
18	2.27	0.0	0.0	0.0		15.1	
19	2.29	0.0	0.0	0.0		16.6	
20	2.32	0.0	0.0	0.0		18.2	
21	2.34	0.0	0.0	0.0		19.8	
22	2.37	0.0	0.0	0.0		21.5	
23	2.40	0.0	0.0	0.0		23.2	
24	2.43	0.0	0.0	0.0		25.0	
25	2.45	0.0	0.0	0.0		26.8	
26	2.48	0.0	0.0	0.0		28.7	
27	2.51	0.0	0.0	0.0		30.7	
28	2.54	0.0	0.0	0.0		32.6	
29	2.57	0.0	0.0	0.0		34.7	
30	2.60	0.0	0.0	0.0		36.8	
31	2.63	0.0	0.0	0.0		38.9	
32	2.66	0.0	0.0	0.0		41.2	
33	2.69	0.0	0.0	0.0		43.6	
34	2.72	0.0	0.0	0.0		45.8	

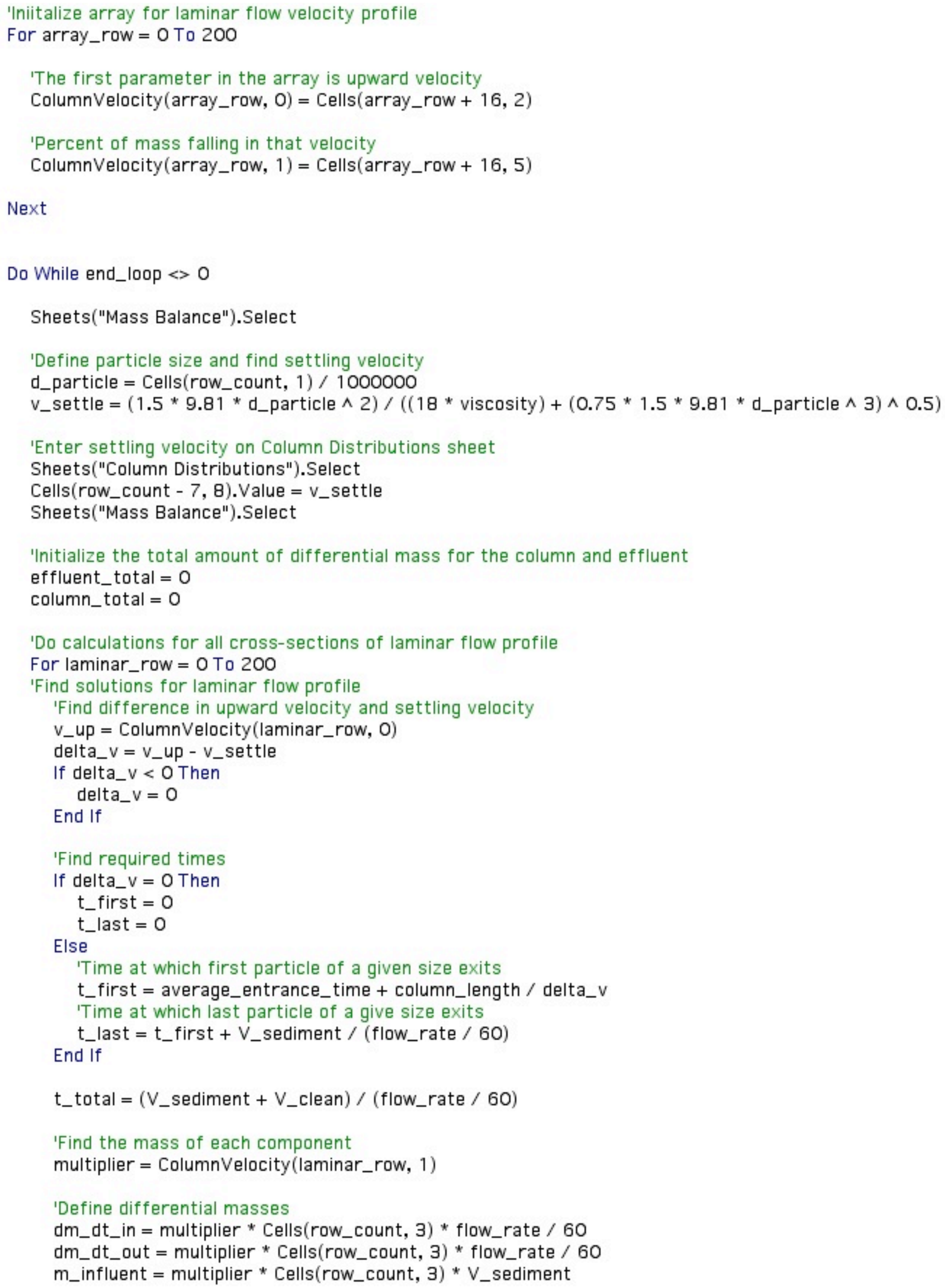
Figure F.4. Column Distributions sheet to store information about particles retained in each column.

F.3. Visual Basic for Applications Code Used in Elutriation Device Program

The following section shows the Visual Basic for Applications (VBA) code that runs the spreadsheet program.

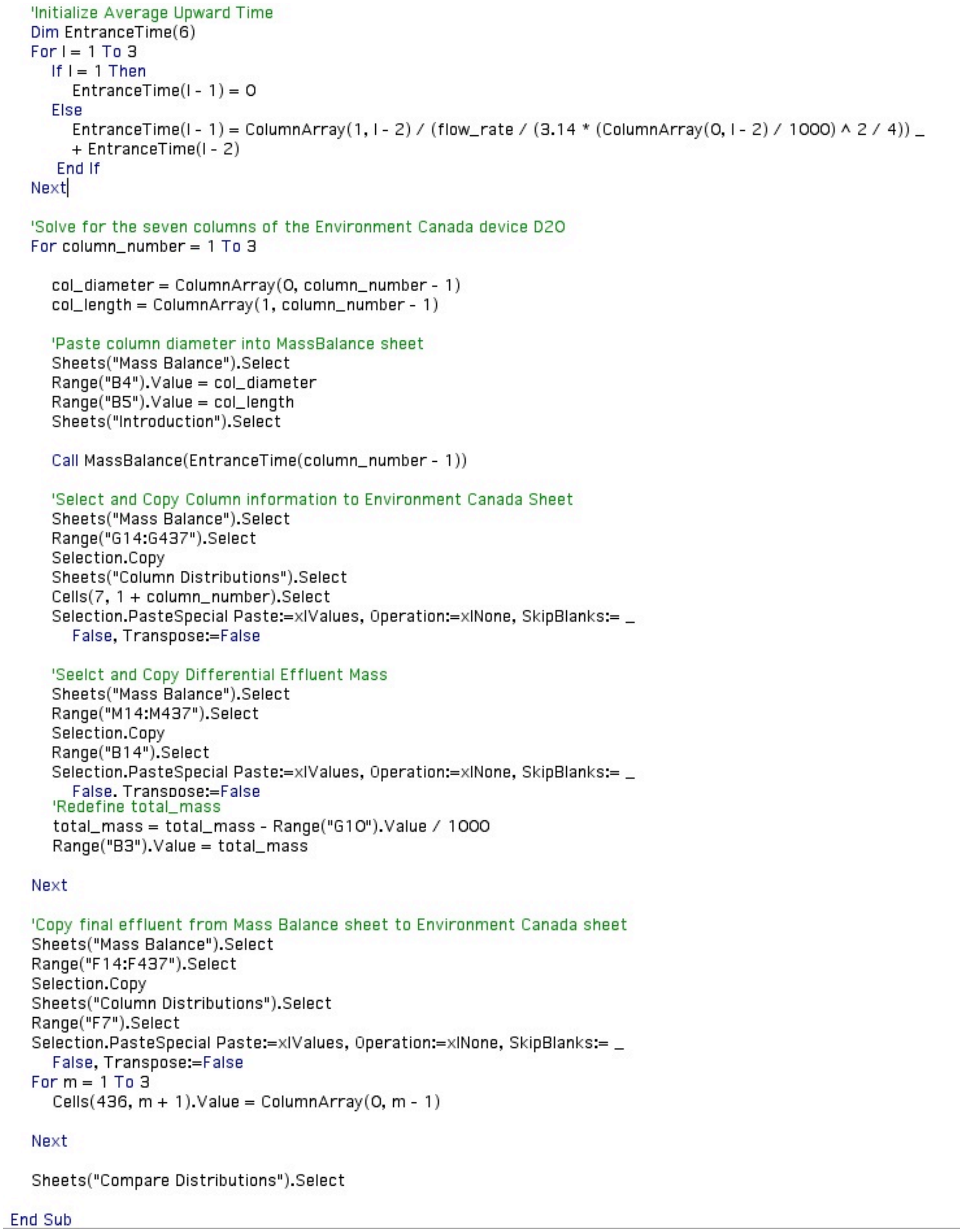


```
Sub MassBalance(average_entrance_time)

Application.ScreenUpdating() = False

'Open Mass Balance Sheet
Sheets("Mass Balance").Select

'Define loop parameters
row_count = 14
end_loop = Cells(row_count, 1).Value

'Initialize important variables
column_length = Range("B5").Value
flow_rate = Range("E3").Value
column_area = ((Range("B4").Value / 1000) ^ 2 * 3.14159 / 4)
vel_avg = flow_rate / 60000 / column_area
V_sediment = Range("E4").Value
V_clean = Range("E5").Value
viscosity = Range("H5").Value * 10 ^ -6

'Define Array of Values
Sheets("Laminar Flow").Select
Dim ColumnVelocity(200, 1) As Variant
```

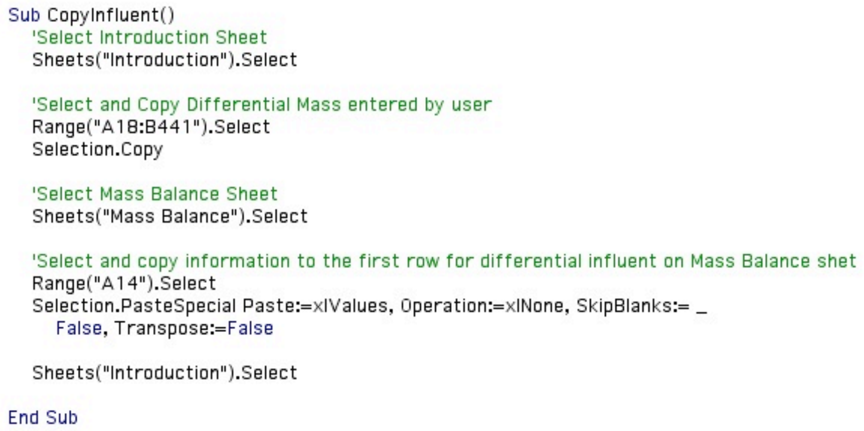


```
'Iniitalize array for laminar flow velocity profile
For array_row = 0 To 200

    'The first parameter in the array is upward velocity
    ColumnVelocity(array_row, 0) = Cells(array_row + 16, 2)

    'Percent of mass falling in that velocity
    ColumnVelocity(array_row, 1) = Cells(array_row + 16, 5)

Next


Do While end_loop <> 0

    Sheets("Mass Balance").Select

    'Define particle size and find settling velocity
    d_particle = Cells(row_count, 1) / 1000000
    v_settle = (1.5 * 9.81 * d_particle ^ 2) / ((18 * viscosity) + (0.75 * 1.5 * 9.81 * d_particle ^ 3) ^ 0.5)

    'Enter settling velocity on Column Distributions sheet
    Sheets("Column Distributions").Select
    Cells(row_count - 7, 8).Value = v_settle
    Sheets("Mass Balance").Select

    'Initialize the total amount of differential mass for the column and effluent
    effluent_total = 0
    column_total = 0

    'Do calculations for all cross-sections of laminar flow profile
    For laminar_row = 0 To 200
    'Find solutions for laminar flow profile
        'Find difference in upward velocity and settling velocity
        v_up = ColumnVelocity(laminar_row, 0)
        delta_v = v_up - v_settle
        If delta_v < 0 Then
            delta_v = 0
        End If

        'Find required times
        If delta_v = 0 Then
            t_first = 0
            t_last = 0
        Else
            'Time at which first particle of a given size exits
            t_first = average_entrance_time + column_length / delta_v
            'Time at which last particle of a give size exits
            t_last = t_first + V_sediment / (flow_rate / 60)
        End If

        t_total = (V_sediment + V_clean) / (flow_rate / 60)

        'Find the mass of each component
        multiplier = ColumnVelocity(laminar_row, 1)

        'Define differential masses
        dm_dt_in = multiplier * Cells(row_count, 3) * flow_rate / 60
        dm_dt_out = multiplier * Cells(row_count, 3) * flow_rate / 60
        m_influent = multiplier * Cells(row_count, 3) * V_sediment
```

```
        'If the total time is less than time required to move to top of column
        If t_first > t_total Or delta_v = 0 Then
            m_effluent = 0
            m_column = m_influent
        End If

        'If the total times is greater than the time required to flush all sediment
        If t_last < t_total And delta_v <> 0 Then
            m_column = 0
            m_effluent = m_influent
        End If


        'If the total time is between the time required to flush all sediment and time required to move to top of column
        If t_first < t_total And t_last > t_total Then
            'm_effluent = (dm_dt_out * (t_total - t_first))
            m_effluent = m_influent * (t_total - t_first) / (t_last - t_first)
            m_column = m_influent - m_effluent
        End If

        'Define total masses
        effluent_total = effluent_total + m_effluent
        column_total = column_total + m_column

    Next

        'Set values in columns in chart
        Cells(row_count, 4).Value = column_total
        Cells(row_count, 5).Value = effluent_total

        'Increment row_count and redefined end_loop
        end_loop = Cells(row_count + 1, 1).Value
        row_count = row_count + 1

Loop


End Sub

Sub SolveDistributions()
    Application.ScreenUpdating() = False

    'Call CopyInfluent sub
    Call CopyInfluent

    'Define Total Mass
    Sheets("Introduction").Select
    total_mass = Range("E11").Value
    Sheets("Mass Balance").Select
    Range("B3").Value = total_mass

    'Initialize ColumnArray Array
    Sheets("Introduction").Select
    Dim ColumnArray(1, 2)
    For k = 1 To 3
        'Column Diameter
        ColumnArray(0, k - 1) = Cells(18 + k, 6)
        'Column Length
        ColumnArray(1, k - 1) = Cells(18 + k, 8)
    Next

    'Find Flow Rate
    flow_rate = Range("B11") / 1000 / 60
```



```
   'Initialize Average Upward Time
   Dim EntranceTime(6)
   For I = 1 To 3
      If I = 1 Then
         EntranceTime(I - 1) = 0
      Else
         EntranceTime(I - 1) = ColumnArray(1, I - 2) / (flow_rate / (3.14 * (ColumnArray(0, I - 2) / 1000) ^ 2 / 4)) _
         + EntranceTime(I - 2)
       End If
   Next

   'Solve for the seven columns of the Environment Canada device D20
   For column_number = 1 To 3

      col_diameter = ColumnArray(0, column_number - 1)
      col_length = ColumnArray(1, column_number - 1)

      'Paste column diameter into MassBalance sheet
      Sheets("Mass Balance").Select
      Range("B4").Value = col_diameter
      Range("B5").Value = col_length
      Sheets("Introduction").Select

      Call MassBalance(EntranceTime(column_number - 1))

      'Select and Copy Column information to Environment Canada Sheet
      Sheets("Mass Balance").Select
      Range("G14:G437").Select
      Selection.Copy
      Sheets("Column Distributions").Select
      Cells(7, 1 + column_number).Select
      Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
         False, Transpose:=False

      'Seelct and Copy Differential Effluent Mass
      Sheets("Mass Balance").Select
      Range("M14:M437").Select
      Selection.Copy
      Range("B14").Select
      Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
         False, Transpose:=False
      'Redefine total_mass
      total_mass = total_mass - Range("G10").Value / 1000
      Range("B3").Value = total_mass

   Next

   'Copy final effluent from Mass Balance sheet to Environment Canada sheet
   Sheets("Mass Balance").Select
   Range("F14:F437").Select
   Selection.Copy
   Sheets("Column Distributions").Select
   Range("F7").Select
   Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
      False, Transpose:=False
   For m = 1 To 3
      Cells(436, m + 1).Value = ColumnArray(0, m - 1)

   Next

   Sheets("Compare Distributions").Select

End Sub
```



```
Sub CopyInfluent()
   'Select Introduction Sheet
   Sheets("Introduction").Select

   'Select and Copy Differential Mass entered by user
   Range("A18:B441").Select
   Selection.Copy

   'Select Mass Balance Sheet
   Sheets("Mass Balance").Select

   'Select and copy information to the first row for differential influent on Mass Balance shet
   Range("A14").Select
   Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
      False, Transpose:=False

   Sheets("Introduction").Select

End Sub
```

Appendix G: Program for Back Calculating Results of Elutriation Device

G.1. Written Description of Program

Description: A program was created in Microsoft Excel using Visual Basic for Applications. The program estimates the actual setting velocity distribution of particles passed through the Elutriation Device. The elutriation device requires a program to back calculate results because the distribution of particles in each column of the device mimics the distribution if a laminar flow profile in the column is assumed.

Program Inputs:

- Mass retained in each column
- Mass measured in effluent
- Column diameters (d_{column})
- Column lengths (l_{column})
- Device high flow rate ($Q_{device-high}$)
- Device low flow rate ($Q_{device-low}$)
- Volume of water/sediment mixture pumped through device ($V_{sediment}$)
- Volume of clean water pumped through device (V_{clean})
- Temperature (to determine density and viscosity of water)

Program Assumptions:

1) The water/sediment mixture is well mixed so the concentration of each particle size is the same throughout the suspension.
2) When particles enter the device, they become evenly distributed across the cross-sectional area of the columns.
3) Particle size distribution between the equivalent settling velocities of the various columns is linearly distributed.

Program Details for Back Calculating of Results:

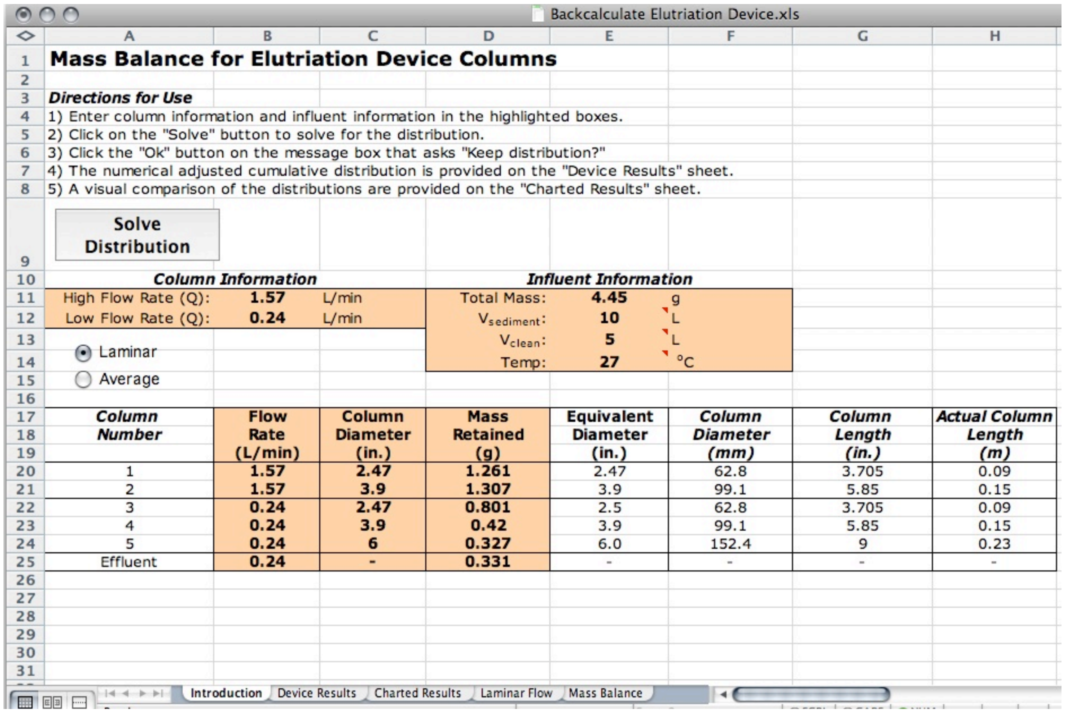
1) Various particle sizes ranging from 1 micron to 1,000 microns are entered into the program with various size increments. The upper limit can be increased if particles in the distribution are expected to be larger than 1,000 microns.
2) The settling velocity of each particle size is estimated using an assumed density and the Ferguson and Church (2004) equation.
3) For each individual particle size, the probability of that particle being retained in each column for each flow rate is calculated. For example the smaller diameter columns operating at a higher flow rate will retain almost none of the very small (<5 micrometer) particles. The specific values are calculated using the equations and methods described in Appendix C.
4) The differential percentages of particle mass retained in each column are used as the initial estimate for particles retained in each column assuming a uniform flow profile in the program.
5) Assuming particle settling velocity distributions between two subsequent columns are linearly distributed, the differential percentage of mass in each column is translated to a differential mass percentage for each of the individual particle sizes described in step 1.
6) For each column, the probability of an individual particle size being retained in that column is multiplied by the estimated differential mass percentage associated with that particle size. The percentages are summed for each column across the entire particle size range. The combination of the parameters generates an estimated differential mass percentage for each individual column. The differential mass percentage is based on the assumption that the columns mimic laminar flow.
7) The Solver function in Excel is used to change the estimated values for actual differential mass that would be retained in each column if the device operated under uniform flow conditions. The results from the elutriation device run are compared to the values determined in step 6. The Solver program continues to change the estimated values for actual differential

mass retained in each column until the difference between the experimental results match up with the theoretical values calculated in step 6.

8) Once the program is complete, a velocity distribution for particles passed through the elutriation device are provided as an output. This settling velocity distribution is the true settling velocity distribution of particles initially taken from the sample.

G.2. Layout of Spreadsheets Used in Program

The spreadsheet program back-calculates the actual settling velocity distribution from device results when the device is operated at two flow rates. The program utilizes four different worksheets for its calculations. The first worksheet (Introduction) is pictured in Figure G.1. The user directly inputs information about the columns, the device operation, and the mass retained in each column. Other worksheets include a worksheet that calculates the velocity at various points across the column cross section (Laminar Flow), a worksheet that calculates the probability of particles retained in each column (Mass Balance), and a worksheet that calculates the actual settling velocity distributions of the influent particles (Device Results). The layout of the worksheets are pictured in Figure G.2., Figure G.3., and Figure G.4., respectively.



Mass Balance for Elutriation Device Columns

Directions for Use

1) Enter column information and influent information in the highlighted boxes.
2) Click on the "Solve" button to solve for the distribution.
3) Click the "Ok" button on the message box that asks "Keep distribution?"
4) The numerical adjusted cumulative distribution is provided on the "Device Results" sheet.
5) A visual comparison of the distributions are provided on the "Charted Results" sheet.

Column Information

High Flow Rate (Q): **1.57** L/min
Low Flow Rate (Q): **0.24** L/min

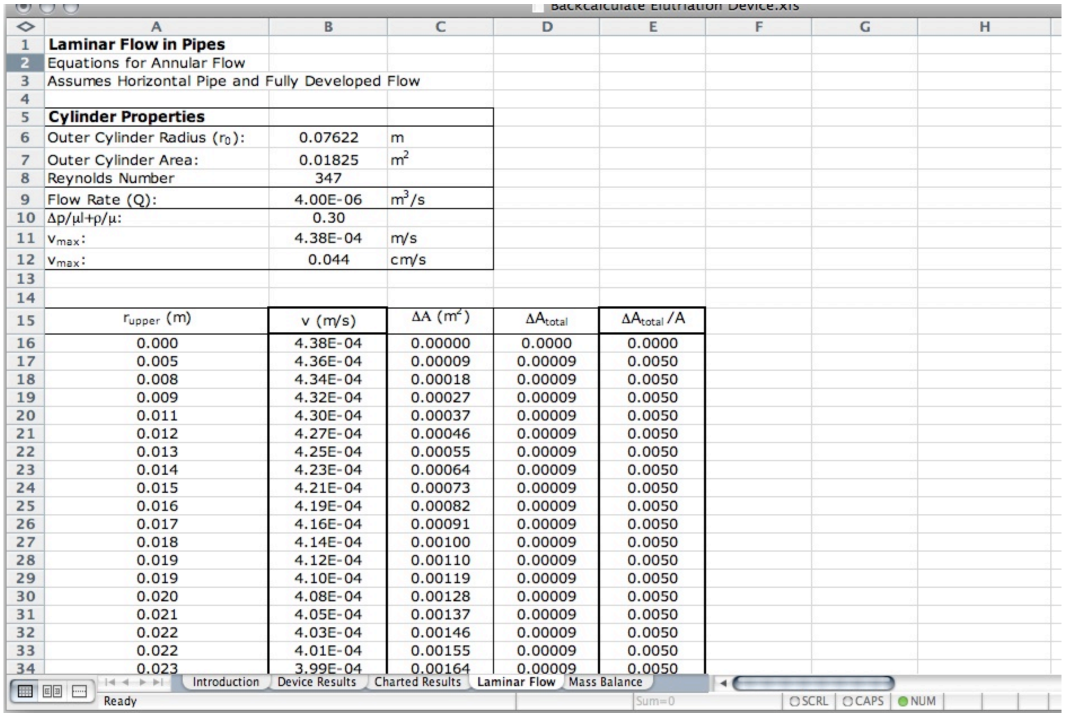
● Laminar
○ Average

Influent Information

Total Mass: **4.45** g
$V_{sediment}$: **10** L
V_{clean}: **5** L
Temp: **27** °C

Column Number	**Flow Rate (L/min)**	**Column Diameter (in.)**	**Mass Retained (g)**	**Equivalent Diameter (in.)**	*Column Diameter (mm)*	*Column Length (in.)*	*Actual Column Length (m)*
1	**1.57**	**2.47**	**1.261**	2.47	62.8	3.705	0.09
2	**1.57**	**3.9**	**1.307**	3.9	99.1	5.85	0.15
3	**0.24**	**2.47**	**0.801**	2.5	62.8	3.705	0.09
4	**0.24**	**3.9**	**0.42**	3.9	99.1	5.85	0.15
5	**0.24**	**6**	**0.327**	6.0	152.4	9	0.23
Effluent	**0.24**	**-**	**0.331**	-	-	-	-

Figure G.1. Introduction sheet for inputting information about elutriation device.

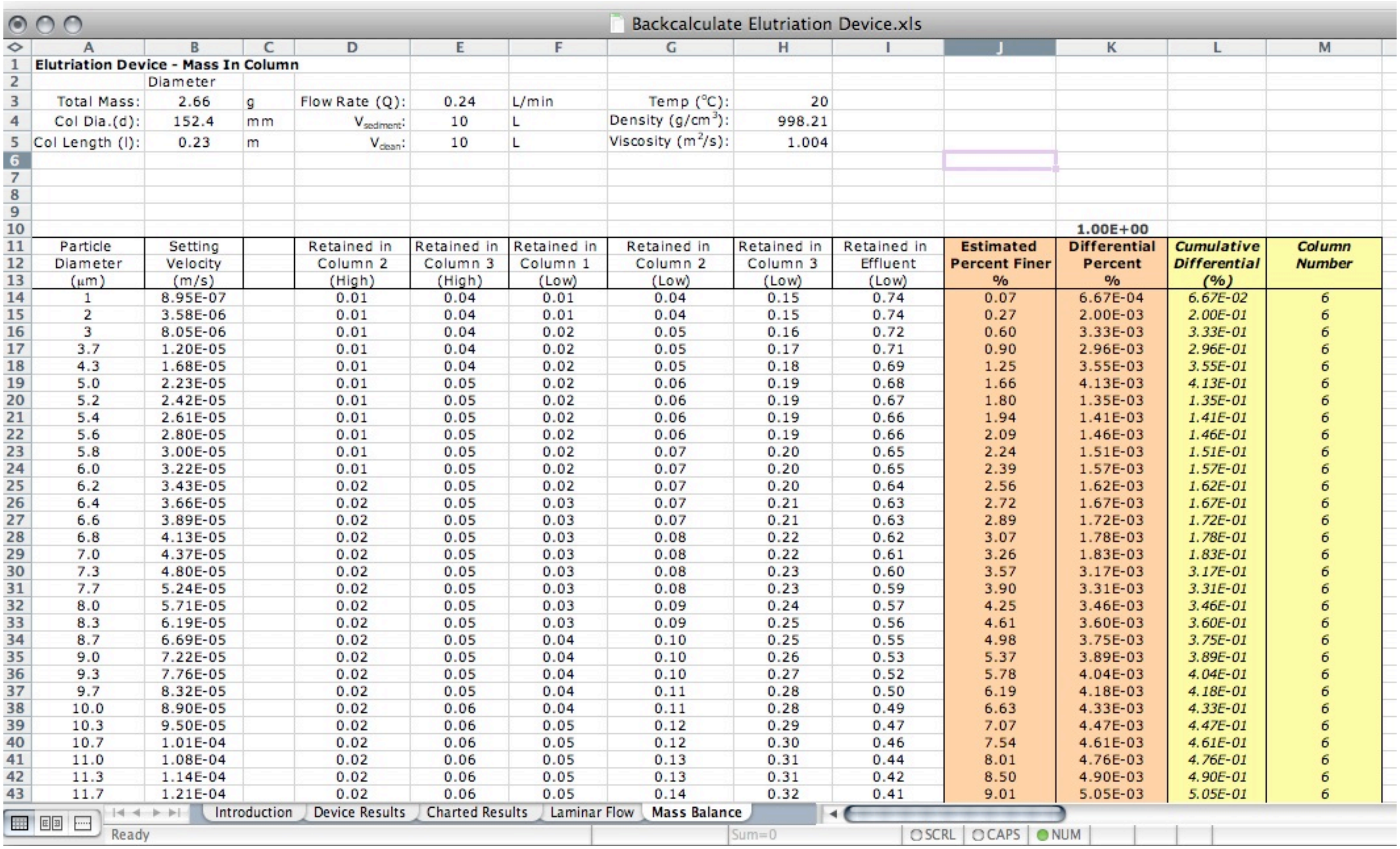


Laminar Flow in Pipes
Equations for Annular Flow
Assumes Horizontal Pipe and Fully Developed Flow

Cylinder Properties		
Outer Cylinder Radius (r_0):	0.07622	m
Outer Cylinder Area:	0.01825	m^2
Reynolds Number	347	
Flow Rate (Q):	4.00E-06	m^3/s
$\Delta p/\mu l+\rho/\mu$:	0.30	
v_{max}:	4.38E-04	m/s
v_{max}:	0.044	cm/s

r_{upper} (m)	v (m/s)	ΔA (m^2)	ΔA_{total}	$\Delta A_{total}/A$
0.000	4.38E-04	0.00000	0.0000	0.0000
0.005	4.36E-04	0.00009	0.00009	0.0050
0.008	4.34E-04	0.00018	0.00009	0.0050
0.009	4.32E-04	0.00027	0.00009	0.0050
0.011	4.30E-04	0.00037	0.00009	0.0050
0.012	4.27E-04	0.00046	0.00009	0.0050
0.013	4.25E-04	0.00055	0.00009	0.0050
0.014	4.23E-04	0.00064	0.00009	0.0050
0.015	4.21E-04	0.00073	0.00009	0.0050
0.016	4.19E-04	0.00082	0.00009	0.0050
0.017	4.16E-04	0.00091	0.00009	0.0050
0.018	4.14E-04	0.00100	0.00009	0.0050
0.019	4.12E-04	0.00110	0.00009	0.0050
0.019	4.10E-04	0.00119	0.00009	0.0050
0.020	4.08E-04	0.00128	0.00009	0.0050
0.021	4.05E-04	0.00137	0.00009	0.0050
0.022	4.03E-04	0.00146	0.00009	0.0050
0.022	4.01E-04	0.00155	0.00009	0.0050
0.023	3.99E-04	0.00164	0.00009	0.0050

Figure G.2. Laminar Flow sheet to determine upward velocity at points within column.



Backcalculate Elutriation Device.xls

Elutriation Device - Mass In Column

Diameter

Total Mass: 2.66 g
Col Dia.(d): 152.4 mm
Col Length (l): 0.23 m

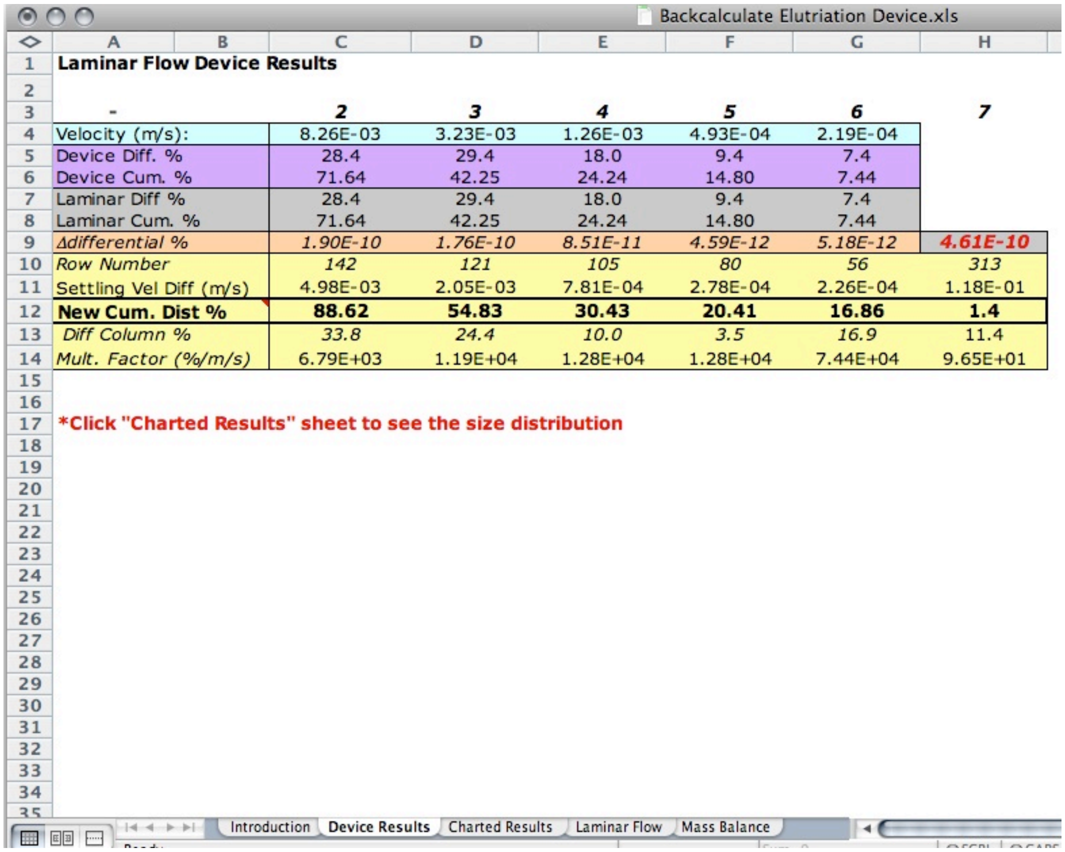
Flow Rate (Q): 0.24 L/min
$V_{sediment}$: 10 L
V_{clean}: 10 L

Temp (°C): 20
Density (g/cm^3): 998.21
Viscosity (m^2/s): 1.004

1.00E+00

Particle Diameter (µm)	Setting Velocity (m/s)	Retained in Column 2 (High)	Retained in Column 3 (High)	Retained in Column 1 (Low)	Retained in Column 2 (Low)	Retained in Column 3 (Low)	Retained in Effluent (Low)	**Estimated Percent Finer %**	**Differential Percent %**	***Cumulative Differential (%)***	***Column Number***
1	8.95E-07	0.01	0.04	0.01	0.04	0.15	0.74	0.07	6.67E-04	6.67E-02	6
2	3.58E-06	0.01	0.04	0.01	0.04	0.15	0.74	0.27	2.00E-03	2.00E-01	6
3	8.05E-06	0.01	0.04	0.02	0.05	0.16	0.72	0.60	3.33E-03	3.33E-01	6
3.7	1.20E-05	0.01	0.04	0.02	0.05	0.17	0.71	0.90	2.96E-03	2.96E-01	6
4.3	1.68E-05	0.01	0.04	0.02	0.05	0.18	0.69	1.25	3.55E-03	3.55E-01	6
5.0	2.23E-05	0.01	0.05	0.02	0.06	0.19	0.68	1.66	4.13E-03	4.13E-01	6
5.2	2.42E-05	0.01	0.05	0.02	0.06	0.19	0.67	1.80	1.35E-03	1.35E-01	6
5.4	2.61E-05	0.01	0.05	0.02	0.06	0.19	0.66	1.94	1.41E-03	1.41E-01	6
5.6	2.80E-05	0.01	0.05	0.02	0.06	0.19	0.66	2.09	1.46E-03	1.46E-01	6
5.8	3.00E-05	0.01	0.05	0.02	0.07	0.20	0.65	2.24	1.51E-03	1.51E-01	6
6.0	3.22E-05	0.01	0.05	0.02	0.07	0.20	0.65	2.39	1.57E-03	1.57E-01	6
6.2	3.43E-05	0.02	0.05	0.02	0.07	0.20	0.64	2.56	1.62E-03	1.62E-01	6
6.4	3.66E-05	0.02	0.05	0.03	0.07	0.21	0.63	2.72	1.67E-03	1.67E-01	6
6.6	3.89E-05	0.02	0.05	0.03	0.07	0.21	0.63	2.89	1.72E-03	1.72E-01	6
6.8	4.13E-05	0.02	0.05	0.03	0.08	0.22	0.62	3.07	1.78E-03	1.78E-01	6
7.0	4.37E-05	0.02	0.05	0.03	0.08	0.22	0.61	3.26	1.83E-03	1.83E-01	6
7.3	4.80E-05	0.02	0.05	0.03	0.08	0.23	0.60	3.57	3.17E-03	3.17E-01	6
7.7	5.24E-05	0.02	0.05	0.03	0.08	0.23	0.59	3.90	3.31E-03	3.31E-01	6
8.0	5.71E-05	0.02	0.05	0.03	0.09	0.24	0.57	4.25	3.46E-03	3.46E-01	6
8.3	6.19E-05	0.02	0.05	0.03	0.09	0.25	0.56	4.61	3.60E-03	3.60E-01	6
8.7	6.69E-05	0.02	0.05	0.04	0.10	0.25	0.55	4.98	3.75E-03	3.75E-01	6
9.0	7.22E-05	0.02	0.05	0.04	0.10	0.26	0.53	5.37	3.89E-03	3.89E-01	6
9.3	7.76E-05	0.02	0.05	0.04	0.10	0.27	0.52	5.78	4.04E-03	4.04E-01	6
9.7	8.32E-05	0.02	0.05	0.04	0.11	0.28	0.50	6.19	4.18E-03	4.18E-01	6
10.0	8.90E-05	0.02	0.06	0.04	0.11	0.28	0.49	6.63	4.33E-03	4.33E-01	6
10.3	9.50E-05	0.02	0.06	0.05	0.12	0.29	0.47	7.07	4.47E-03	4.47E-01	6
10.7	1.01E-04	0.02	0.06	0.05	0.12	0.30	0.46	7.54	4.61E-03	4.61E-01	6
11.0	1.08E-04	0.02	0.06	0.05	0.13	0.31	0.44	8.01	4.76E-03	4.76E-01	6
11.3	1.14E-04	0.02	0.06	0.05	0.13	0.31	0.42	8.50	4.90E-03	4.90E-01	6
11.7	1.21E-04	0.02	0.06	0.05	0.14	0.32	0.41	9.01	5.05E-03	5.05E-01	6

Figure G.3. Mass Balance sheet to calculate probabilities of particles settling in each column.



Laminar Flow Device Results

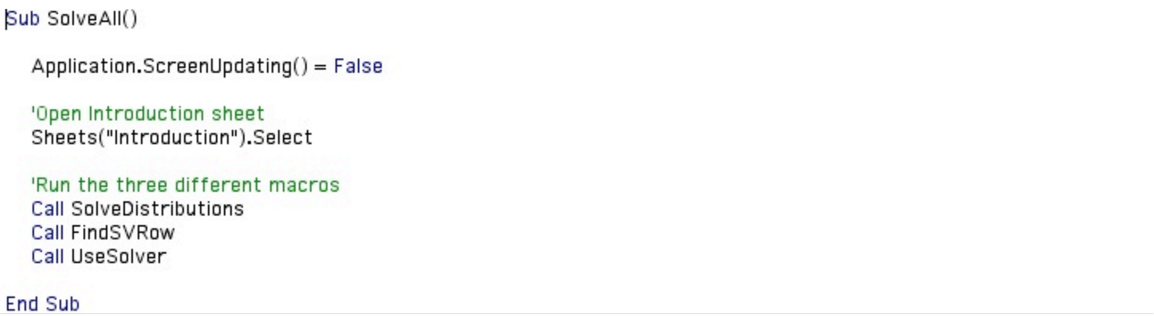
	A–B	C	D	E	F	G	H
1	**Laminar Flow Device Results**						
2							
3	-	**2**	**3**	**4**	**5**	**6**	**7**
4	Velocity (m/s):	8.26E-03	3.23E-03	1.26E-03	4.93E-04	2.19E-04	
5	Device Diff. %	28.4	29.4	18.0	9.4	7.4	
6	Device Cum. %	71.64	42.25	24.24	14.80	7.44	
7	Laminar Diff %	28.4	29.4	18.0	9.4	7.4	
8	Laminar Cum. %	71.64	42.25	24.24	14.80	7.44	
9	*Δdifferential %*	*1.90E-10*	*1.76E-10*	*8.51E-11*	*4.59E-12*	*5.18E-12*	***4.61E-10***
10	*Row Number*	*142*	*121*	*105*	*80*	*56*	*313*
11	Settling Vel Diff (m/s)	4.98E-03	2.05E-03	7.81E-04	2.78E-04	2.26E-04	1.18E-01
12	**New Cum. Dist %**	**88.62**	**54.83**	**30.43**	**20.41**	**16.86**	**1.4**
13	*Diff Column %*	*33.8*	*24.4*	*10.0*	*3.5*	*16.9*	11.4
14	*Mult. Factor (%/m/s)*	6.79E+03	1.19E+04	1.28E+04	1.28E+04	7.44E+04	9.65E+01

***Click "Charted Results" sheet to see the size distribution**

Figure G.4. Device Results sheet to calculate the actual settling velocity distribution for particles passing through device.

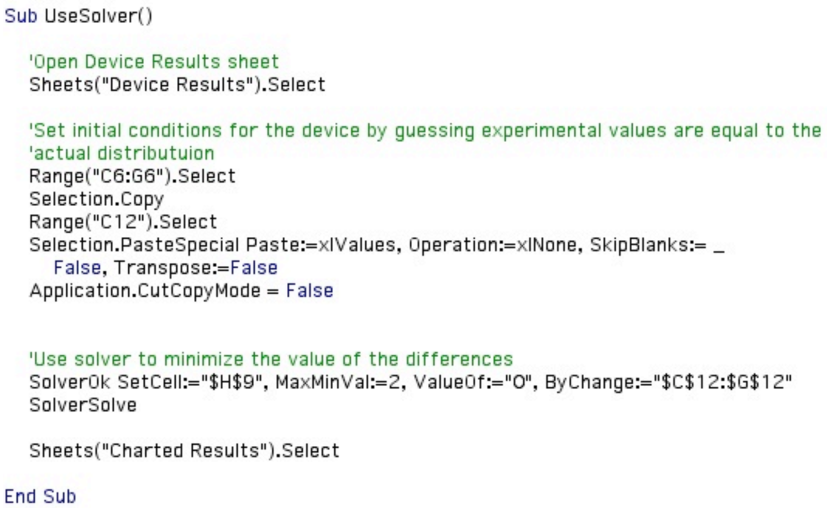
G.3. Visual Basic for Applications Code Used in Elutriation Device Program

The following section shows the Visual Basic for Applications (VBA) code that runs the spreadsheet program.

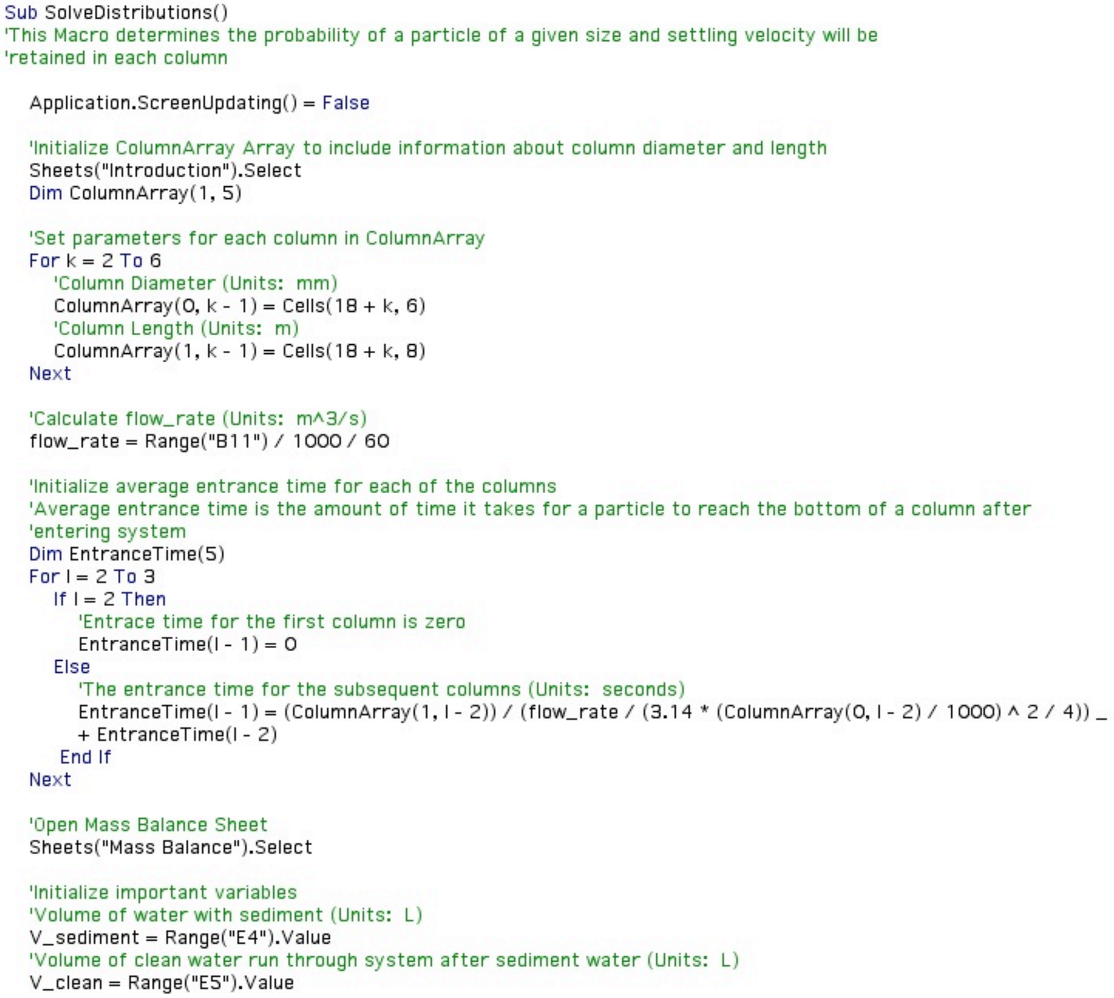


```
Sub SolveAll()

    Application.ScreenUpdating() = False

    'Open Introduction sheet
    Sheets("Introduction").Select

    'Run the three different macros
    Call SolveDistributions
    Call FindSVRow
    Call UseSolver

End Sub
```

```
Sub FindSVRow()

    Application.ScreenUpdating() = False

    'Determine the row number for each of the settling velocities produced by elutriation device
    row_count = 14

    'Determine row on "Mass Balace" that corresponds to column upward velocity for each column
    For column_num = 6 To 2 Step -1

        'Select Device Results sheet
        Sheets("Device Results").Select
        'Define average settling velocity from elutriation device column
        settling_velocity = Cells(4, column_num + 1)

        'Initialize row_count and end_loop variable
        end_loop = 1

        'Select Mass Balance sheet
        Sheets("Mass Balance").Select

        'Loop until the settling velocity of the column is exceeded
        Do While end_loop <> 0

            'If the settling velocity of the particle is greater than the average column velocity
            'then increase the value of row_count by one
            If Cells(row_count, 2).Value < settling_velocity Then
                row_count = row_count + 1
                Cells(row_count, 13).Value = column_num
            'Otherwise set end_loop to zero to terminate the Do While loop
            Else
                end_loop = 0
            End If
        Loop

        'Open Device Results sheet
        Sheets("Device Results").Select

        'Enter the corresponding row information to cells in Device Results sheet
        Cells(10, column_num + 1).Value = row_count
        Cells(12, column_num + 1).Value = Cells(6, column_num + 1)
    Next

    'Open Device Results sheet
    Sheets("Device Results").Select

    'Enter the total row numbers in cell
    end_for_large_loop = Range("H10").Value

    'Enter a value of 7 for particles that will be flushed through to effluent
    For large_particle_count = (row_count + 1) To end_for_large_loop
        Sheets("Mass Balance").Select
        Cells(large_particle_count, 13).Value = 7
    Next


End Sub
```



```
Sub UseSolver()

    'Open Device Results sheet
    Sheets("Device Results").Select

    'Set initial conditions for the device by guessing experimental values are equal to the
    'actual distributuion
    Range("C6:G6").Select
    Selection.Copy
    Range("C12").Select
    Selection.PasteSpecial Paste:=xlValues, Operation:=xlNone, SkipBlanks:= _
        False, Transpose:=False
    Application.CutCopyMode = False


    'Use solver to minimize the value of the differences
    SolverOk SetCell:="$H$9", MaxMinVal:=2, ValueOf:="0", ByChange:="$C$12:$G$12"
    SolverSolve

    Sheets("Charted Results").Select

End Sub
```



```
Sub SolveDistributions()
'This Macro determines the probability of a particle of a given size and settling velocity will be
'retained in each column

    Application.ScreenUpdating() = False

    'Initialize ColumnArray Array to include information about column diameter and length
    Sheets("Introduction").Select
    Dim ColumnArray(1, 5)

    'Set parameters for each column in ColumnArray
    For k = 2 To 6
        'Column Diameter (Units:  mm)
        ColumnArray(0, k - 1) = Cells(18 + k, 6)
        'Column Length (Units:  m)
        ColumnArray(1, k - 1) = Cells(18 + k, 8)
    Next

    'Calculate flow_rate (Units:  m^3/s)
    flow_rate = Range("B11") / 1000 / 60

    'Initialize average entrance time for each of the columns
    'Average entrance time is the amount of time it takes for a particle to reach the bottom of a column after
    'entering system
    Dim EntranceTime(5)
    For l = 2 To 3
        If l = 2 Then
            'Entrace time for the first column is zero
            EntranceTime(l - 1) = 0
        Else
            'The entrance time for the subsequent columns (Units:  seconds)
            EntranceTime(l - 1) = (ColumnArray(1, l - 2)) / (flow_rate / (3.14 * (ColumnArray(0, l - 2) / 1000) ^ 2 / 4)) _
            + EntranceTime(l - 2)
         End If
    Next

    'Open Mass Balance Sheet
    Sheets("Mass Balance").Select

    'Initialize important variables
    'Volume of water with sediment (Units:  L)
    V_sediment = Range("E4").Value
    'Volume of clean water run through system after sediment water (Units:  L)
    V_clean = Range("E5").Value
```

```
'Kinematic viscosity of the water based on temperature (Units:  m^2/s)
viscosity = Range("H5").Value * 10 ^ -6

'Initialize array to calculate amount of mass remaining in each size range
Dim MassRemaining(300, 1)
For x = 0 To 300
  MassRemaining(x, 0) = 1
  MassRemaining(x, 1) = 1
Next

'Loop to solve for the amount of mass of each particle size retained in the four columns
For column_number = 2 To 3

  'Initialize column diameter from ColumnArray (Units:  mm)
  col_diameter = ColumnArray(0, column_number - 1)
  'Initialize column length from ColumnArray (Units:  m)
  col_length = ColumnArray(1, column_number - 1)
  'Initialize column area from column diameter (Units:  m^2)
  column_area = ((col_diameter / 1000) ^ 2 * 3.14159 / 4)
  'Calculate the average upward velocity in each column (Units:  m/s)
  vel_avg = flow_rate / column_area

  'Paste column diameter and column length into MassBalance sheet
  Sheets("Mass Balance").Select
  Range("B4").Value = col_diameter
  Range("B5").Value = col_length
  Range("E3").Value = flow_rate * 60000


  'Define array of upward velocity and average mass values for laminar flow
  Sheets("Laminar Flow").Select
  Dim ColumnVelocity(199, 1) As Variant
  For array_row = 0 To 199
    'The first parameter in the array is upward velocity (Units:  m/s)
    ColumnVelocity(array_row, 0) = Cells(array_row + 16, 2)
    'Percent of mass falling in that velocity (Units:  unitless)
    'Percent of mass is calculated by delta_area between two radii divided by total area
    ColumnVelocity(array_row, 1) = Cells(array_row + 16, 5)
  Next

  'Open Mass Balance sheet
  Sheets("Mass Balance").Select
  'Initilize a variable to determine when the loop reaches the end of the defined particle sizes
end_loop = Range("A14").Value
'Initializes a variable to count the rows
row_count = 14

'Solve for differential percentage retained in the column as long as a particle size is defined
Do While end_loop <> 0

  'Open Mass Balance sheet
  Sheets("Mass Balance").Select

  'Initialize particle diameter value (Units: m)
  d_particle = Cells(row_count, 1) / 1000000
  'Initilize settling velocity of particle with diamter d_particle and SG = 2.65 (Units:  m/s)
  v_settle = (1.65 * 9.81 * d_particle ^ 2) / ((18 * viscosity) + (0.75 * 1.65 * 9.81 * d_particle ^ 3) ^ 0.5)
  'Insert settling velocity values into spreadsheet
  Cells(row_count, 2) = v_settle

  'Initialize the total mass retained in effluent and column
  effluent_total = 0
  column_total = 0
```

```
'Loop through the various segments of the laminar flow profile defined in Laminar Flow sheet
For laminar_row = 0 To 199

   'Initialize upward velocity from the ColumnVelocity array (Units:  m/s)
   v_up = ColumnVelocity(laminar_row, 0)
    'Calculate difference in upward velocity and settling velocity (Units:  m/s)
   delta_v = v_up - v_settle

   'If the upward velocity is less than the particle settling velocity, set delta_v to zero
   If delta_v < 0 Then
      delta_v = 0
   End If

   'If the upward velocity is less than the settling velocity, t_first and t_last are set to zero
   If delta_v = 0 Then
      t_first = 0
      t_last = 0
   Else
      'Calculate amount of time required for a particle to exit the column (Units:  s)
      t_first = EntranceTime(column_number - 1) + (col_length) / delta_v
      'Calculate the time at which hte very last particle exits the column (Units:  s)
      t_last = t_first + V_sediment / 1000 / (flow_rate)
   End If


   'Find the total amount of time the device is operated (Units:  s)
   t_total = (V_sediment + V_clean) / 1000 / (flow_rate)

   'Find the mass of particles in the componenet associated with the lamianr flow velocity
   multiplier = ColumnVelocity(laminar_row, 1)

   'Calculate the amount of particles in the size range related to the laminar flow velocity
   m_influent = multiplier * MassRemaining(row_count - 14, 0)

   'If the total time is less than time required for a particle to move to the top of the column
   'then every single particle is retained in the respective column and none exit to effluent
   If t_first > t_total Or delta_v = 0 Then
      m_effluent = 0
      m_column = m_influent
   End If


   'If the total operation time is greater than the amount of time for all particles to exit the column
   'then none of the particles will be retained in the column
   If t_last < t_total And delta_v <> 0 Then
      m_column = 0
      m_effluent = m_influent
   End If

   'If the total time is between the time required to flush all sediment and time required to move to top of column
   'then some particles will leave in effluent and some will remain in column
   If t_first < t_total And t_last > t_total Then
      'The mass of the effluent is equal to the mass of the influent times the proprtion of the different between
      'the total time and the first particle exiting and the different between the  time required for the last
      'particle to exit the column and the first particle to enter the column
      m_effluent = m_influent * (t_total - t_first) / (t_last - t_first)
      m_column = m_influent - m_effluent
   End If

   'Differential effluent and column masses for the specific laminar flow velocity are added to the total
   'influent and effluent masses
   effluent_total = effluent_total + m_effluent
   column_total = column_total + m_column

Next
```

```
'Paste column diameter and column length into MassBalance sheet
Sheets("Mass Balance").Select
Range("B4").Value = col_diameter
Range("B5").Value = col_length


'Define array of upward velocity and average mass values for laminar flow
Sheets("Laminar Flow").Select

'Loop through the upward velocities for different cross sections of the laminar flow profile
For array_row = 0 To 199
  'The first parameter in the array is upward velocity (Units:  m/s)
  ColumnVelocity(array_row, 0) = Cells(array_row + 16, 2)
  'Percent of mass falling in that velocity (Units:  unitless)
  'Percent of mass is calculated by delta_area between two radii divided by total area
  ColumnVelocity(array_row, 1) = Cells(array_row + 16, 5)
Next

'Open Mass Balance sheet
Sheets("Mass Balance").Select
'Initilize a variable to determine when the loop reaches the end of the defined particle sizes
end_loop = Range("A14").Value
'Initializes a variable to count the rows
row_count = 14

  'Solve for differential percentage retained in the column as long as a particle size is defined
  Do While end_loop <> 0
  'Open Mass Balance sheet
  Sheets("Mass Balance").Select

  'Initialize particle diameter value (Units: m)
  d_particle = Cells(row_count, 1) / 1000000
  'Initilize settling velocity of particle with diamter d_particle and SG = 2.65 (Units:  m/s)
  v_settle = (1.65 * 9.81 * d_particle ^ 2) / ((18 * viscosity) + (0.75 * 1.65 * 9.81 * d_particle ^ 3) ^ 0.5)
  'Insert settling velocity values into spreadsheet
  Cells(row_count, 2) = v_settle

  'Initialize the total mass retained in effluent and column
  effluent_total = 0
  column_total = 0

  'Loop through the various segments of the laminar flow profile defined in Laminar Flow sheet
  For laminar_row = 0 To 199
  'Initialize upward velocity from the ColumnVelocity array (Units:  m/s)
  v_up = ColumnVelocity(laminar_row, 0)
   'Calculate difference in upward velocity and settling velocity (Units:  m/s)
  delta_v = v_up - v_settle

  'If the upward velocity is less than the particle settling velocity, set delta_v to zero
  If delta_v < 0 Then
    delta_v = 0
  End If

  'If the upward velocity is less than the settling velocity, t_first and t_last are set to zero
  If delta_v = 0 Then
    t_first = 0
    t_last = 0
  Else
    'Calculate amount of time required for a particle to exit the column (Units:  s)
    t_first = EntranceTime(column_number - 1) + (col_length) / delta_v
    'Calculate the time at which hte very last particle exits the column (Units:  s)
    t_last = t_first + V_sediment / 1000 / (flow_rate)
  End If
```

```
                'Find the total amount of time the device is operated (Units:  s)
                t_total = (V_sediment + V_clean) / 1000 / (flow_rate)

                'Find the mass of particles in the componenet associated with the lamianr flow velocity
                multiplier = ColumnVelocity(laminar_row, 1)

                'Calculate the amount of particles in the size range related to the laminar flow velocity
                m_influent = multiplier * MassRemaining(row_count - 14, 0)

                'If the total time is less than time required for a particle to move to the top of the column
                'then every single particle is retained in the respective column and none exit to effluent
                If t_first > t_total Or delta_v = 0 Then
                    m_effluent = 0
                    m_column = m_influent
                End If


                'If the total operation time is greater than the amount of time for all particles to exit the column
                'then none of the particles will be retained in the column
                If t_last < t_total And delta_v <> 0 Then
                    m_column = 0
                    m_effluent = m_influent
                End If

                'If the total time is between the time required to flush all sediment and time required to move to top of column
                'then some particles will leave in effluent and some will remain in column
                If t_first < t_total And t_last > t_total Then
                    'The mass of the effluent is equal to the mass of the influent times the proprtion of the different between
                    'the total time and the first particle exiting and the different between the  time required for the last
                    'particle to exit the column and the first particle to enter the column
                    m_effluent = m_influent * (t_total - t_first) / (t_last - t_first)
                    m_column = m_influent - m_effluent
                End If

                'Differential effluent and column masses for the specific laminar flow velocity are added to the total
                'influent and effluent masses
                effluent_total = effluent_total + m_effluent
                column_total = column_total + m_column

            Next
            'Save the value for the previous MassRemaining(x,0) to MassRemaining(x,1)
            MassRemaining(row_count - 14, 1) = MassRemaining(row_count - 14, 0)
            'Recalculate the value for MassRemaining(x,0) by subtracting total amount retained in individual column
            MassRemaining(row_count - 14, 0) = MassRemaining(row_count - 14, 0) - column_total
            'Record values of differential mass for each particle size on the spreadsheet
            Cells(row_count, column_number + 2) = MassRemaining(row_count - 14, 1) - MassRemaining(row_count - 14, 0)
            'Increase the value of row_count by 1
            row_count = row_count + 1
            'Check to see if the loop is at the end of the line
            end_loop = Cells(row_count, 1).Value

        Loop
    Next

    Sheets("Device Results").Select
    Range("H10").Value = row_count - 1
    Range("H5").Value = flow_rate

End Sub
```