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Design of a pneumatic conveying test loop for laboratory testing

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Design of a Pneumatic Conveying Test Loop for Laboratory Testing

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Abstract

Pneumatic conveying is the transportation of material through a closed conveying line in a gas medium via a pressure differential. In industry, pneumatic conveying is used extensively to handle materials: specifically, bulk solids and powders. 80% of all transported materials are bulk solids and pneumatic conveying is currently experiencing industry growth at a rate of 6.4% annually. Industrial pneumatic conveyor suppliers use specialized testing systems to make design decisions regarding specific applications, taking into account the conveyed material, the structure of the plant in which the system will be installed, and desired system characteristics such as necessary filtering or safety requirements. As interest in material conveying characteristics grows so does the demand for small-scale testing facilities. This paper explores the development of a highly versatile pneumatic conveying test loop for small-scale materials conveying characterization.

This system is equipped with instrumentation which allows for data to be gathered regarding the velocity of particles in the flow, the pressure differential across the system, and the mass flow rate of air and material through the system. This allows for the change in material properties as well as system damage due to conveying to be analyzed. A pipeline with a 53 mm bore and a 41 m equivalent length, including 9 long radii 90° elbows, is specified. Additional system components discussed include a rotary air compressor, feeding hopper, rotary air lock feeder and filters for material separation. Instrumentation applied to this system includes a laser Doppler velicometer, which allows for particle velocities to be determined, a sight glass, which allows for flow phase to be determined, a pressure transducer, which allows for pressure changes in the system to be determined, a Coulombmeter, which allows for electrostatic charge build up in a system test section to be determined, and a hot wire anemometer, which allows for the velocity of air in the system to be measured before the introduction of conveyed material.

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Nomenclature

Δp - The change is pressure (kN/m^2 or Bar)

f - Darcy Friction Factor (Unitless)

d - Pipeline Bore (Inner Diameter) (m or mm)

ρ - Density (kg/m^3)

C - Velocity (m/s)

P - Pressure (kN/m^2 or Bar or Psig of kPa)

T - Temperature (K)

R- Individual Gas Constant (J/kgK or kJ/kgK)

$\dot{m}_a$- Mass Flow Rate Air (kg/s)

ψ – Pipeline Friction Coefficient (unitless)

k- Head Loss Coefficient Bend (unitless)

m_p- Mass Flow Rate of Material (tonne/hr e.g. Metric Ton/hr)

L_e - Equivalent Conveying Length (m)

L_{eb}- Equivalent Conveying Length of Bends (m)

μ- dynamic viscosity of fluid (kg/ m*s)

h- Horizontal Conveying Distance (m)

V- Vertical Conveying Distance (m)

N-Number of Bends in System

A_F- Area of Filter (m^2)

γ^*- Gas to Cloth Ratio

$\dot{V}$- Volumetric Flow Rate of Air (m^3/s)

* subscripts a refer to air, numerical subscripts refer to outlet and inlet conditions of system

Introduction

Pneumatic conveying is the transportation of material through a closed conveying line in a gas medium via a pressure differential. In industry, pneumatic conveying is used extensively to handle materials, specifically bulk solids and powders. A wide array of materials can be conveyed from fly ash to polymer pellets [1]. 80% of all transported materials are bulk solids and pneumatic conveying is currently experiencing industry growth at a rate of 6.4% annually.

When compared to mechanical conveying, pneumatic conveying is advantageous due to its enclosed system design, which allows for its easy integration into existing site architecture and reduces material loss. Pneumatic conveyors have a minimal number of moving components as compared to mechanical conveyors, reducing average lifetime maintenance costs. Pneumatic conveying is also an ideal choice when considering environmental factors as its enclosed nature reduces pollution caused by material degradation in open systems and allows for the conveyance of materials that must be contained due to environmental concerns [1].

In designing pneumatic conveying systems, testing of a specific material in a test apparatus to establish material conveying properties is more useful than theoretical design techniques. Industrial pneumatic conveyor suppliers use specialized testing systems to make design decisions regarding specific applications, considering the conveyed material, the structure of the plant in which the system will be installed, and desired system characteristics, such as necessary filtering or safety requirements. The natures of these test apparatuses vary widely. Common characteristics of existing devices include vertical and horizontal sections, an air mover, bends that mimic installation site geometry, a feeding device, and a material disengagement device [3,4]. These systems are regularly equipped with instrumentation which allows for data to be gathered regarding the velocity of particles in flow, the pressure differential across the system, and the mass flow rate of air and material through the system. This allows for the change in material properties as well as system damage due to conveying to be analyzed. Information regarding the abrasive wear on the system, particle attrition, material water loss through the system, flow regimes, material cohesiveness, minimum conveying velocity and material flow phase can then be determined [1].

Industry leaders consult directly with customers to design pneumatic conveying systems that are suited for their purposes. During consultation, these companies offer services including materials characterization for conveying and testing via full–scale simulation in which the supplier mimics the geometry of the client's system and carries out full-scale testing [1].

Project Objective

The primary objective of this departmental honors thesis is to develop and theoretically validate a design for a pneumatic conveying test loop with instrumentation that will allow for the collection data regarding abrasion of the system by the material, abrasion of the material by the system, material friability or particle attrition, flow rate of the material in the system, and flow characteristics throughout the system in a laboratory setting. The objective of this project was identified by the projects client E and G Associates Inc., an engineering consulting and contract research firm based in Chattanooga, TN that works primarily in the powder processing industry [5]. The desired test loop will ideally be able to carry out testing on materials with particle sizes varying from 10 mm to 1 micrometer with realistic criteria being identified as particle sizes varying from 1 mm to 50 micrometers. The transportation medium in this system will be air. The air supply pressure is limited in this project to a 64 cfm (or 108.73 m^3/h) at 125 psig (or 862 kPa) by the existing screw compressor.

Background

Types of Conveying Systems

In this project two systems of pneumatic conveying will be considered: positive pressure (push) and negative pressure (vacuum) systems. These systems are differentiated by the displacement method they use to convey material, with positive pressure systems utilizing positive displacement and negative pressure systems conveying material via a vacuum [1].

Positive pressure systems are the most common type of pneumatic conveying system in use. These systems "push" conveyed material through the system discharging the material at atmospheric pressure. Depending on conveying distance, these systems can require high pressure, as it is important to ensure that the system can push the conveyed solid through the longest pipe configuration. These systems are well suited for one pick-up location and multiple collection locations [1].

Negative pressure systems utilize a positive displacement vacuum pump downstream of the conveying system to "pull" conveyed material through the system. These are well suited for multiple pick up locations and one collection location. They allow for dust free and "leak free" systems [6].

Types of Conveying: Dilute and Dense Flow

In this project, two types of pneumatic conveying will be considered: dilute and dense phase conveying [7]. The average density of the conveyed particles in the conveying line differentiates these systems. To make this distinction, the solids loading ratio (ϕ) is established [8]. This is a ratio of the mass flow rate of the conveyed solid $\dot{m}_p$ to the mass flow rate of the air $\dot{m}_a$ in the flow.

The solids loading ratio of dilute phase systems ranges between 0 and 15. These systems are characterized using large volumes of conveying gas at high velocity and operate at comparatively low pressure differential. In these systems, solids are carried by the conveying gas as discrete units through the action of lift and drag forces. The lowest air velocity in the system is at the pick-up point as static material is drawn into the system. The velocity of the air at this point is one of the most important design considerations in the system, as the material must become instantaneously entrained in the airflow. In general, the conveying line inlet air velocity to dilute phase systems vary between 13-15 m/s [1].

The solids loading ratio of dense phase systems is greater than 15. Comparatively low gas velocities and high pressure differentials characterize dense flow systems. In a dense flow situation, the distribution of the conveyed solid is not uniform in the conveying pipe as the velocity of the conveying gas is less than what is necessary to suspended conveyed particles in the flow. This results in behavior where traditional conveying takes place in the upper section of the pipe and in the lower portion of the pipe a very dense group of particles moves as a layer at a lower velocity. This flow can range from stable (smooth conveying) to unstable (extreme pressure changes). There are many modes by which solids can move in dense phase systems including as a plug that completely packs the conveying pipe. These systems sometimes employ secondary gas injectors in the system line to remove plugs and reduce the required system gas velocity [1]. Dense phase conveying does not occur in vertical conveying.

Standard System Components

Pneumatic conveying systems traditionally consist of five major subsystems: the material storage device, the prime mover, the feeding apparatus, the conveying line, and the material disengagement apparatus [1].

Prime Mover

The prime mover is the device that provides the gas medium at a pressure to the system. The prime mover is specified based on system requirement of volumetric airflow and pressure**.** These values are primarily dependent of the characteristics of the material being conveyed (such as minimum conveying velocity) and the conveying line distance. Types of prime movers include fans, blowers, compressors, and plant air systems. For dense phase or long distance dilute phase systems, a screw or reciprocating compressor is suitable. For short distance dilute phase conveying, a fan or blower is suitable [1]. As this system is intended to convey a range of materials, the prime mover selected has to have high pressure and high volumetric output capabilities.

Positive displacement compressors are prime movers that have high pressure and volumetric output capabilities. These systems are resistant to pressure surges in the conveying system as pressure surges in the system only slightly reduce volumetric air flow from a positive displacement compressor. Most compressors deliver high temperature air. Generally, this air is cooled, which may increase the moisture content. Rotary screw compressors are one of the most commonly applied positive displacement compressor types. Rotary screw compressors consist of intermeshing rotors mounted on shafts in parallel. The action of air being trapped between these rotors compresses the air and as rotation continues allows the compressed air to escape through the outlet. A wide range of capabilities can be achieved by screw compressors from as low as 4 m^3/min to as high as 700 m^3/min. Maximum pressures of 9 bar can be achieved.

Feeding Apparatus

The feeding apparatus is the device or series of devices that introduce the material being conveyed into the conveying gas stream. As the conveying material is at rest when it is introduced into the gas stream, there is a significant change in the momentum of the conveyed material in a very short time. To ensure consistent material handling, many systems implement an area in which the conveyed solid can accelerate to a steady flow and therefore be carried uniformly in the flow. Generally, there are two types of feeding systems: controlled feed systems, for which the amount of solid introduced into the conveyor can be carefully controlled, and non-controlled feeding systems, for which the amount of solid that is being picked up by the system cannot be easily controlled. Controlling the rate at which solids are added to the system is important when carrying out testing; however, many commercial systems do not use controlled feeding systems. The mass flow rate through the system can be monitored via instrumentation regardless of the type of feeding system. The sealing function of the feeding system to the conveying line is important, as the component that contributes the most pressure loss in the system is typically the feeder. This is due to turbulence in the feeding zone as particles accelerate when they are added to the flow. There are three pressure classifications for commercially available feeders: low pressure (up to 100 kPa), medium pressure (up to 300 kPa) and high pressure (up to 1,000 kPa). Due to the 792 kPa rating of the provided system compressor, the developed apparatus will act as high pressure system. Criteria against which feeding systems are chosen include the properties of the particles being transported, the space available for the system, if the system in intended for continuous operation, feeding rate (controlled or non-controlled feeding), and conveying pressure [1].

Popular types of feeders for forward pressure systems are screw feeders, rotary valves, and blow tanks. Screw feeders are hard to implement as it is challenging to feed against the pressure gradient. Screw feeders are advantageous in that there exists a linear relationship between screw speed and the feed rate making metering material into the system easy. Similarly, rotary valves inherently meter material by nature of their design as rotor pockets are filled with a known amount of material. Rotary valve feeders require venting to account for air leakage. These designs regularly use entrainment sections, zones that allow for straight line acceleration of conveyed material. Blow tanks are well suited for high-pressure systems and batch conveying, though they may be modified to allow for continuous conveying. They have no moving parts and are therefore well suited to friable materials. Blow tanks can be disadvantageous, as they required significant insulation site headroom and cause a pressure drop in the system; however, they can convey a wide variety of materials. For negative pressure or vacuum systems, suction nozzles act as feeding devices. There is almost no pressure difference across the feeder because the operating pressure is atmospheric in vacuum systems. Therefore the system does not experience pressure loss due to the feeder [1].

Rotary valves are the most suitable feeder for systems with hoppers that have circular outlets. They consist of a rotor with blades that rotate within a stationary housing and regularly act as an airlock. To ensure uniform feeding from a storage hopper, a vertical circular section should be installed between the feeder and the hopper.

Conveying Line

The conveying line traditionally consists of piping, which acts as the enclosed space through which the material is conveyed. This section can be vertical or horizontal and will contain bends of various radii. Pipe material selection requires the analysis of many factors, including the pressure the pipe will see, the abrasiveness of the conveyed material, the reactivity of the conveyed material, the size of the conveyed particles, operating temperature, and cost. Typical materials include stainless steel, galvanized steel, aluminum and carbon. Special treatments can be applied to materials to reduce corrosion. Many fittings are available for piping, standard bends include the short and long radius bends, where the short radius bends correlate to a bends with a split line radius of three to five times the pipe outer diameter and long radius bends correlate to bends with a split line radius that is approximately eight times the pipeline outer diameter. To prevent blockages in the conveying line, industry best practices dictate that the inside diameter of the conveying pipe should be at minimum three times the size of the maximum conveyed material size.

This is the portion of the system where diverging areas that may consist of bends or other diverting systems will redirect flow. When flow is redirected, its characteristics change, namely it decelerates and is no longer in steady state flow; therefore, conveyed materials can drop out of flow. These areas contribute significantly to material damage in conveying. To avoid such issues, acceleration zones can be added to systems after bends or other divergent areas. This must be considered carefully in the design of this system as the footprint of the system is limited by existing laboratory space [5].

Material Separation Device

The material disengagement apparatus is the system by which conveyed materials are removed from the gas stream. The design and selection of these components is relevant as the collector can cause damage to the material, especially if the material has any particularly reactive properties such as being hydrophilic, thermally reactive, or highly susceptible to crushing. Additionally, the collecting area must not be forgotten in instrumenting the system, as it is prime way in which the mass flow rate of the system can be analyzed via real time massing. In many cases a filter or a fan may decelerate the flow of the conveyed particles. In this design, a filter receiver is being considered [1].

Filter receivers utilize fabric filters to separate particles from gas flow in vacuum and forward pressure systems. These systems are well suited for the conveyance of fine particles. Filters can cause pressure loses in the system and must be carefully sized. Additionally, adverse chemical and physical interaction caused by the filter material must be considered in selection. Filter receivers must have incorporated cleaning systems that regularly clear the filter of residual particulate; this system can be pneumatic, sonic, or vibratory in operation [1].

Existing Test System Designs

Common characteristics of existing test systems include variable feeding capabilities, variable conveying line diameters, vertical and horizontal conveying sections, bends of various radii, variable feeding systems used for different flow phases and pressure systems, instrumentation, and computer-based data acquisition systems. Many pilot plant systems attempt to mimic the geometry and conditions of the proposed industrial site.

In figure 1 below, an example of a pilot plant test rig utilized by *Tel-Tek* to perform pneumatic conveying test can be seen.

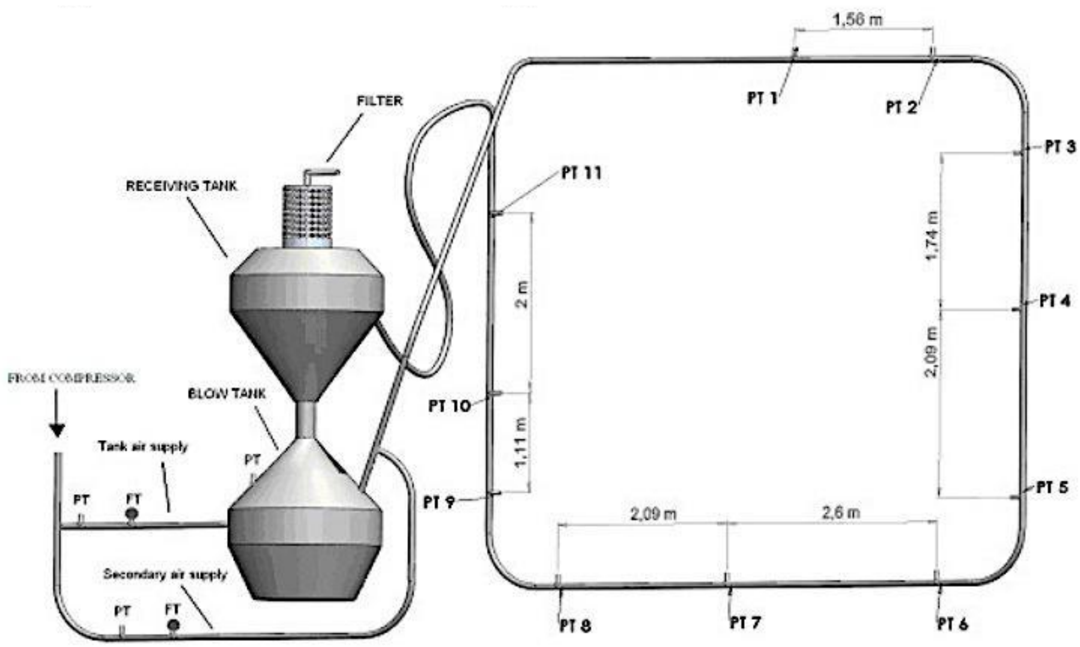

Figure 1: Tel-Tek Pilot Plant System [3]

This system is equipped with a 0.4 m^3 capacity blow tank with a pressure rating of 8 bar. The 58 mm diameter conveying line has a total length of 26 m with a 13 m vertical section. In figure 1, “PT” represents pressure transducers and “FT” represents gas flow meters, this system utilizes 11 pressure transducers throughout the conveying line. The conveying medium in this system is air and the primary air mover is a compressor. A filter receiver is utilized in this system as the material separation device [3].

NOL-TEC systems describe in their test facility profile and cost guidelines some characteristics and capabilities of their pilot plant system. Their system is made of mild steel with an aluminum vacuum hopper. Available conveying line setups for dilute phase positive pressure and vacuum systems include 2 in x 100 ft conveying line with 6 90° bends and 2 45° bends, 3 in x 50 ft conveying line with 2 90° bends, 1 30° bend, and 1 60° bend, 3 in x 100 ft or 200 ft conveying line with 6 or 7 90° bends, and 3 in x 400 ft conveying line with 6 90° bends. Setups available for dense phase vacuum include all the previously mentioned setups, excluding the 3 in x 400 ft set up and additionally a 5 in x 100 ft conveying line with 6 90° bends. In their dense phase vacuum conveying tests, a vacuum blower acts as the air mover, a 10 ft^3 feed hopper is used to store test material in the rig, gas assists may be installed along the conveying line, and material is weighed both before and after the test via load cells on receiving and storage hoppers. In their dilute phase forward pressure conveying tests, material is stored in a 10 ft^3 feed hopper and then fed into a 3-inch rotary airlock, a screw feeder is available to meter the amount of material added to the system, the receiver in the system is a 50 ft^3 receiving bin with a dust filter, the material is weighed both before and after the test. In these tests, parameters analyzed include conveying rate and conveying line pressure drop, and mass flow of conveying gas [7].

Validation Analysis

Procedures and Results

The first two parameters that are approached in design are conveying line length and pipeline bore. To simplify analysis, these parameters are found using first approximation methods with an air only assumption. These methods allow for pressure loss in the system to be assessed without considering the effects of conveyed material properties, which allows baseline system characteristics to be determined. Air only methods are particularly apt for dilute phase conveying cases, as solids loading ratios are very low. Reasonable system modeling can be carried out using air only approximation methods [8].

In selecting conveying line distance and pipeline bore, a major consideration is system pressure loss, which contributes to demand for free air and therefore system power consumption. First approximation methods can be used to determine air only pressure loss in the pipeline versus pipeline bore and conveying length. These losses are determined via Darcy's equation for both positive and negative pressure systems. Darcy's equation for air only straight-line pressure loss is

$$\Delta p = \frac{4fL}{d} * \frac{\rho C^2}{2} \left(\frac{N}{m^2}\right). \qquad (1)$$

This relationship is dependent on air density, speed, and pipeline characteristics. Noting that air density can be expressed in terms of pressure and temperature via the ideal gas equation

$$\rho = \frac{P}{RT} \qquad (2)$$

and velocity *C* can be expressed in terms of air mass flow rate via equation 3 below,

$$C = \frac{4\dot{m}_a RT}{\pi d^2 p} \left(\frac{m}{s}\right) \qquad (3)$$

the following relationships for air only pressure drop for positive and negative pressure systems respectively can be developed.

$$\Delta p_a = (p_2^2 + \frac{64fL\dot{m}_a^2 RT}{\pi^2 d^5}) - p_2 \quad (\frac{N}{m^2}) \qquad (4)$$

$$\Delta p_a = p_1 - (p_1^2 + \frac{64fL\dot{m}_a^2 RT}{\pi^2 d^5})^{0.5} \quad (\frac{N}{m^2}) \qquad (5)$$

Here, *R* is the specific gas constant for air in J/kg*K, for negative pressure systems p_1 is atmospheric pressure, and for positive pressure systems p_2 is atmospheric pressure. These relationships for air only pressure losses in straight pipes allow for multiple pipeline bore and length relationships regarding system pressure loss to be accessed. Air only pressure loss, determined via Darcy's equation, over a range of pipeline bores and lengths for smooth pipe with a friction factor of 0.0045 are displayed in figures 2 and 3 respectively.

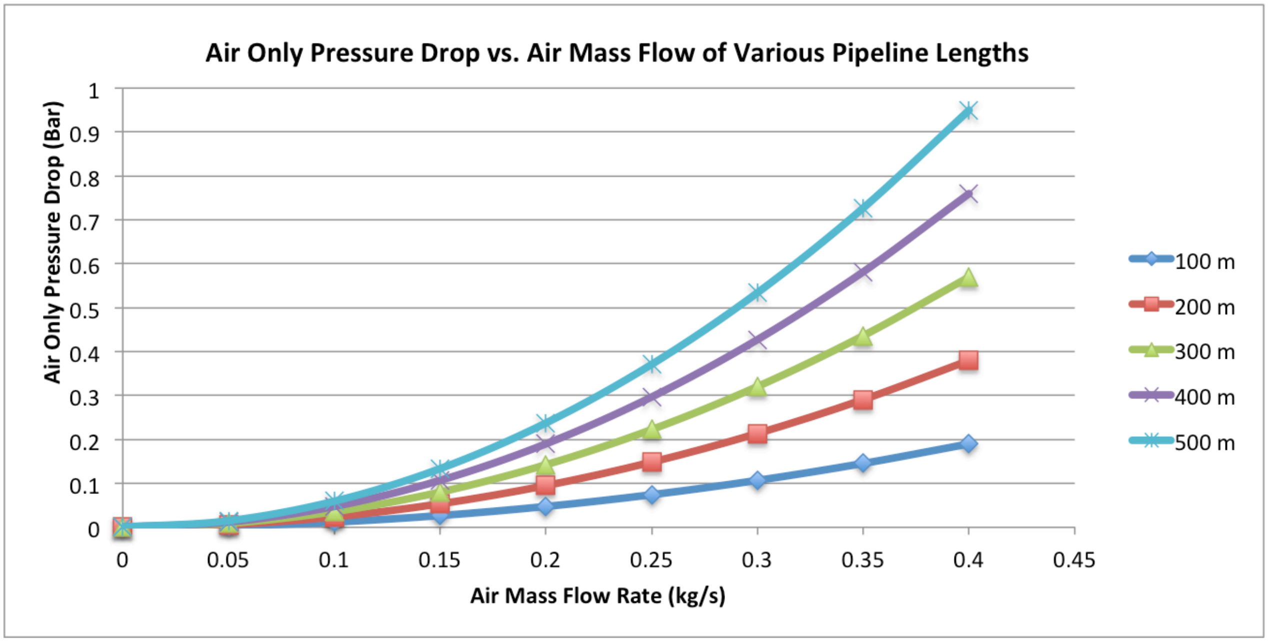

Figure 2: Air Only Pressure Drop at Various Pipe Lengths

In figure 2, the relationship between pressure loss, air mass flow rates (or conveying velocity, as shown in equation 3) and conveying length is seen. Pressure drop can then be seen to increase with increased air mass flow rate and conveying length.

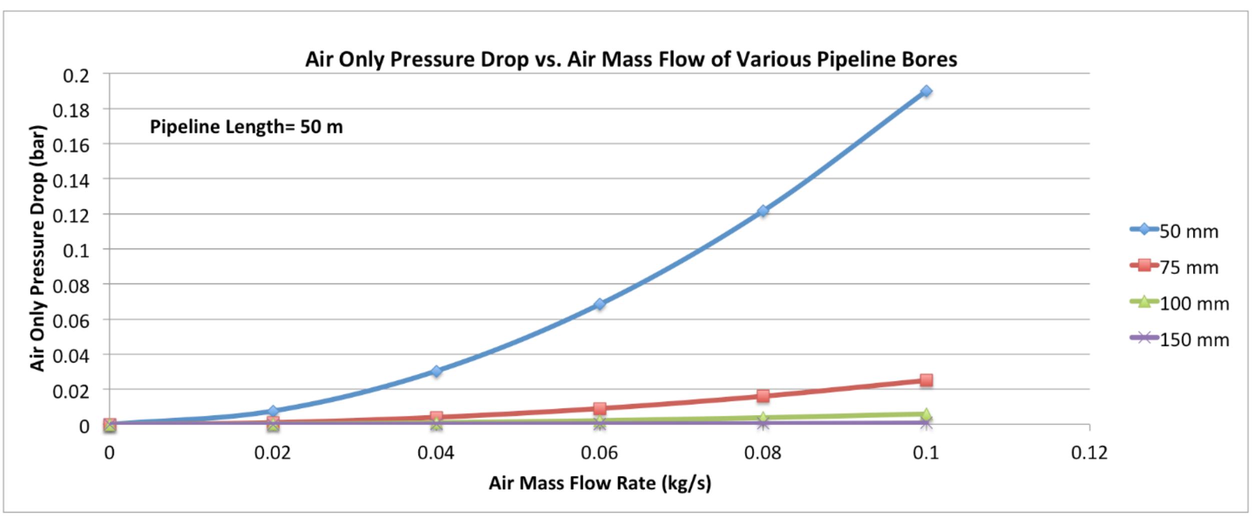

Figure 3: Air Only Pressure Drop at Various Pipe Bores

In figure 3, the relationship between pressure change, air mass flow rates (or conveying velocity as shown in equation 3) and conveying pipeline bore is displayed.

Pressure loss is then seen to increase with increased air mass flow rate and is inversely proportional to conveying pipeline bore.

First approximation methods can additionally be used to approximate the relationship between material mass flow rate, pipeline pressure drop, and pipeline characteristics [8]. The necessary pipeline bore for a set of conveying and pipeline characteristics can be reasonably approximated utilizing relationships for an air only pressure drop in a system. Given a dilute flow system with a conveying length L, a conveying line inlet air velocity that ensures dilute phase flow (a velocity of approximately greater than 13 m/s), and a desired material mass flow rate in tonnes/h, a pipeline bore *d*, can be found with an iterative solution. Using an outlet velocity of the system estimated as

$$C_2 = (1 + estimated\ conveying\ line\ pressure\ drop) * C_1,$$

the air only pressure drop for a positive pressure system is determined via equation 6 below

$$\Delta p_a = p_{atm}[(1 + \frac{\psi C_2^2}{RT_2})^{0.5} - 1] \qquad (6)$$

where *R* is the characteristic gas constant in kJ/kg *K, p_{atm} is atmospheric pressure at which the system exhausts in (kN/m^2), T_2 is the outlet temperature of the system (assumed to be 300 K for analysis), C_2 is the estimated outlet velocity of the system in (m/s), and ψ is pipeline friction loss coefficient, which is calculated via equation 7 below:

$$\psi = \left(\frac{4\,f\,L}{d} + \Sigma k\right) + pipeline\ exit\ loss\ coefficient \qquad (7)$$

where k is the bend loss coefficient, which can be determined from equivalent length analysis. The k coefficient normalizes bends towards horizontal conveying sections such that they can be treated equivalently in analysis. In equation 7, the pipeline exit loss coefficient is assumed to be one [8]. The calculated value for the pipeline friction loss coefficient and an estimated outlet velocity of the system can then be used to calculate the air only pressure drop of the system. This value can then be used to determine the air supply pressure for a positive pressure system via equation 8 below.

$$p = \frac{1}{2}\{p_{atm} + \Delta p_a + [(p_{atm} + \Delta p_a)^2 + \frac{\dot{m_p T_1} \Delta p_a}{2.46 C_1 d^2}]^{\frac{1}{2}}\} \quad (8)$$

where $\dot{m}_p$ is the desired material mass flow rate of the system. The conveying line pressure drop for a positive pressure system can then be approximated by

$$\Delta p_c = p - p_{atm} \quad (9)$$

where Δp_c is the conveying line pressure drop. If this value is similar to the initial estimated system pressure loss, then the selected pipeline bore is appropriate for this set of characteristics [8].

Using this method, pipelines with 35 mm and 53mm bores where analyzed against conveying velocities ranging from 10 m/s to 16 m/s for a 50 m pipe with five 90° bends with bend loss coefficients of 0.02. Approximate material mass flow rate values at given pressure drops in the system vs. conveying velocities were calculated. These values are expressed graphically in figure 4 below.

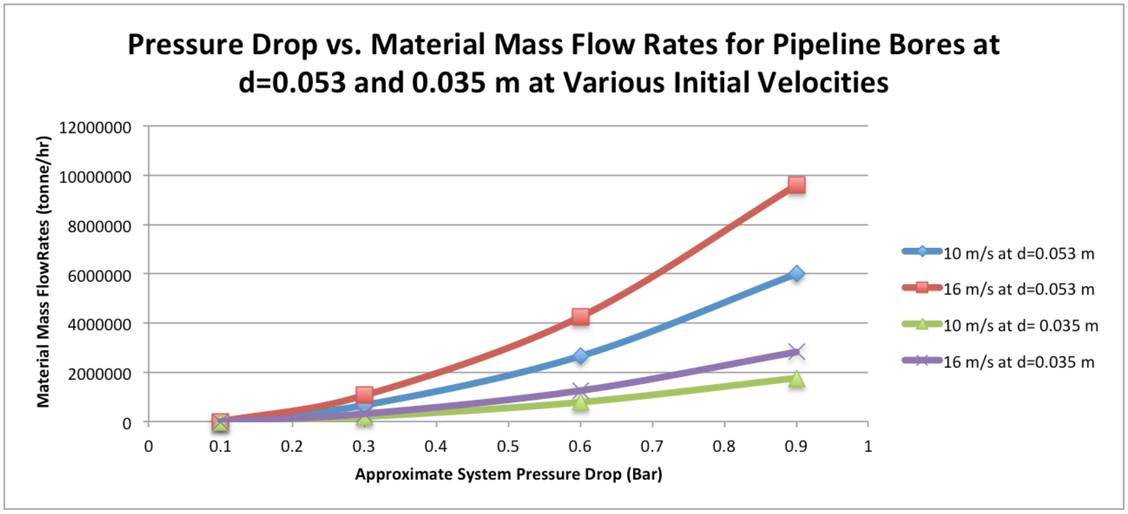

Figure 4: Pressure Drop vs. Material Mass Flow Rates for Pipeline Bores d=0.053 and 0.035 m at various initial velocities

In figure 4, iterative methods were used to estimate material mass flow rates at approximate system pressure drop for pipeline bores. Here it can be seen that with decreased bores there are decreased material mass flow rates at equivalent pressure drops. It is also seen that with increasing system initial velocity, material mass flow rate increases. The material mass flow rates in this analysis are too high to be applicable to this system design; however, they conveniently illustrate the trends.

Through understanding these relationships between air only pressure drop, conveying line length, conveying line bore, and knowledge of existing system with pipeline bores that successfully conveyed a range of materials (*discussed in existing test systems*) a pipeline bore of 53mm was selected. Industry best practice dictate's that the conveying line diameter should be at least six time of the average particle diameter of the conveyed material, meaning this pipeline bore should be sufficient for average particle diameters up to approximately 9 mm; however, existing test systems with this pipeline bore have been shown to be capable of conveying materials with greater average particle diameters in dilute and dense phase [1].

Equivalent Length Analysis

To carry out further analysis of the system at this selected pipeline bore, the length of the conveying line, including bends, horizontal sections and vertical sections, must be reduced to a single parameter. This is referred to as the equivalent length of the conveying line, which normalizes all conveying line components to horizontal conveying such that they can be treated as horizontal conveying sections in analysis. In this analysis, long radius bends (bends with a center line radius that is eight times the conveying line outer diameter) of 90° will be considered [11]. To determine the equivalent length of a bend, the head loss of the bend *k* must be determined. These values are determined experimentally and are found via a chart. In order to determine *k,* the ratio of the bend diameter to pipeline diameter (D/d) must be determined. The value of *k* for 90° bends can then be selected from figure 5 below [8].

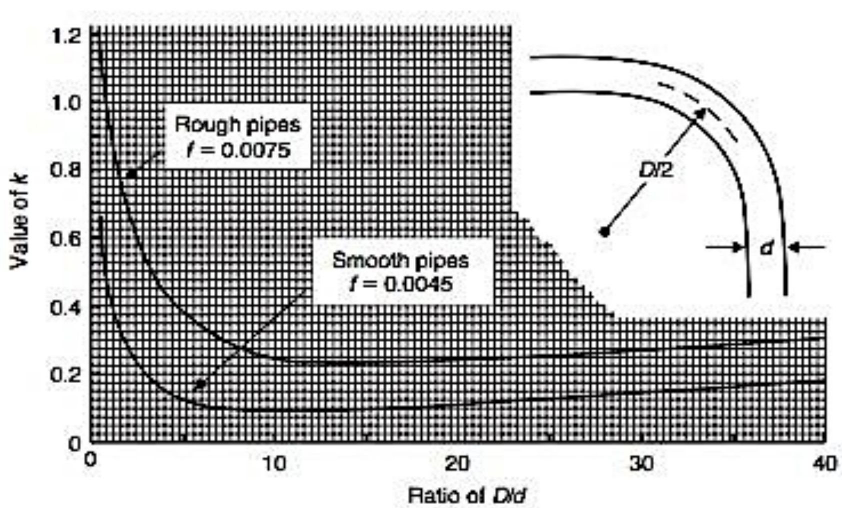

Figure 5: "Head Loss for 90° Radiused Bends" [8]

Once the values are determined, the equivalent length of the bends line can be found with

$$L_{eb} = \frac{kd}{4f}\ (m) \tag{10}$$

where *d* is the pipeline diameter, L_{eb} is the equivalent length of a bend, and *f* is the friction factor of the selected pipe. The friction factor of a pipeline is found via the Reynolds number and pipeline roughness. Typical pipeline surface roughness used for commercial steels and wrought iron pipes is 4.5 μm. The selected surface roughness value is divided by pipeline bore *d* to determine relative roughness.

The Reynolds number can be calculated based on air mass flow rate and pipeline bore of a system via

$$R_e = \frac{4\dot{m}_a}{\pi d\mu} \tag{11}$$

where Re is the Reynolds number, and μ is the dynamic viscosity of air in (kg/m*s). The friction factor is then determined from a Moody Chart utilizing the determined Reynolds number and relative roughness of the pipe.

Given the equivalent lengths of the bends in the system, the equivalent length of the entire conveying line can then be calculated via

$$L_e = h + 2v + N(L_{eb})(m) \tag{12}$$

where L_e is the equivalent length of the entire conveying line, *h* is the horizontal conveying distance in meters, *v* is the vertical conveying distance, and *N* is the number of bends [8].

As the Reynolds number is dependent on the mass flow rate of air, it changes with conveying characteristics. Reynolds numbers for the selected pipeline were calculated over a range of velocities, which were found to be similar enough for their difference to be considered negligible in analysis. A standard smooth pipe friction factor of 0.0045 was then selected for equivalent length analysis.

Using the equivalent length method, the desired conveying system geometry can be reduced to one equivalent length for analysis. In this design system, geometry is constrained by available laboratory space at the instillation site, which is 60 ft. x 20 ft. x 12ft. This limits maximum lengths horizontally and vertically and the maximum height. The system should incorporate both vertical and horizontal conveying, which is achieved through the implementation of standard 90° elbows. Eight elbows where chosen such that the test loop had one 2.44 m vertical section and 33.83 m of horizontal conveying, primarily implemented in two suspended loops. A schedule 40 stainless steel pipeline with a bore of 0.053 m and outer diameter of 0.0603 m was used to determine bend loss coefficients and D/d ratios for standard 90° elbows. Pipeline characteristics and final equivalent length are tabulated below.

Table 1: Pipeline Characteristics [14]

Pipeline Material	40s Stainless Steel	
Inner Diameter (Bore)	0.053	m
Outer Diameter	0.0603	m
Wall Thickness	0.0039	m
Allowable Working Pressure at 300 K	125	Bar
Pipeline Friction Factor (*f*)	0.0045	dimensionless
Number of 90° Bends	8	dimensionless
Horizontal Conveying Distance (h)	33.83	m
Vertical Conveying Distance (v)	2.438	m
Long Radius Elbow, Split line Radius	0.482	m
90° Elbow D/d Ratio	9.00	dimensionless
Bend Loss Coefficient 90°	0.1	dimensionless
Equivalent Length 90° Bends	0.29	m
Total Pipeline Equivalent Length	41	m

Here, stainless steel pipe was selected due to its prevalence in the pneumatic conveying industry and its non-reactive nature, which makes it an ideal choice for an application in which unknown, potentially reactive, materials will be conveyed. Schedule 40s pipe was selected as it is highly available and has working pressure of 125 Bar at approximate room temperature, which exceeds the possible system max pressure [14]. Once system equivalent length and pipeline bore were determined, the system could be validated against the selected validation materials via scaling analysis.

Scaling Analysis

The capability of the system to convey a bulk material is dependent primarily on pipeline bore, conveying length, available pressure, and conveying air velocity [8]. Necessary system characteristics vary due to the properties of conveyed material; however, this variance is not easily predicted. For this reason, material conveying test data is used in the validation of this design. By scaling existing test data to the desired system length or bore given constant system pressure drop and pipeline bore or length respectively, the conveying properties of a material in the system can be determined. Through scaling, the mass flow rate and the solids loading ratio of the material can be identified. If the scaled solids loading ratio does not exceed maximum solids loading ratios seen in existing test data, these theoretical conditions are valid. Similarly, materials have known minimum-conveying velocities for dense and dilute phase flow, and if scaled data exceeds these values, then theoretical data is invalid. Scaling allows the conveying capability of a theoretical system to be validated against bulk solids for which extensive test data exists [8].

The eight materials chosen for validation purposes were ordinary Portland cement, fresh granulated sugar, magnesium sulphate, iron powder, polyethylene pellets, fluorspar**,** wheat flour and coal pearls. These materials were chosen because they represent a wide range on material characteristics, are all capable of being conveyed in dilute phase flow and have extensive publicly available conveying data. Material properties are listed below.

Table 2: Material Characteristics for Chosen Materials [13]

	Mean Particle Size (micrometer)	**Bulk Density (kg/m^3)**	**Particle Density (kg/m^3)**	**Compaction (%)**	**Permeability (m^3s/kg *10^-6)**
Ordinary Portland Cement	14	1070	3060	40	0.71
Granulated Sugar (Fresh)	460	890	1580	10	20
Magnesium Sulphate	370	1380	2355	29	6.3
Iron Powder	64	2380	5710	34	0.34
Fluorspar	66	1580	3700	-	-
Polyethylene Pellets	4000	540	910	5	420
Wheat Flour	90	510	1470	37	1.3
Coal Pearls	10000	690	1320	-	-

These materials span an average particle diameter size from 14 to 10,000 micrometers, percent compaction ranges from 5 to 40, bulk and particle density range from 510-2380 and 910 to 3060 kg/m^3 respectively, and permeability of the materials range from 0.34 to 420 m^3 /kg *10^{-6} [13]. Of these materials, ordinary Portland cement, wheat flour and Iron powder have dense phase flow capability allowing the systems dense phase flow capability to be verified. Further discussion of material selection can be found in *Appendix 2*.

This testing device was designed using an existing compressor, so the conveying capability of the system was restricted by the compressor's available discharge pressure at a given air mass flow rate. This was determined using supplied data and a compressor performance curve. This allowed for the maximum and minimum capabilities determined from scaling to be identified.

An example of this analysis for Ordinary Portland Cement is displayed in figure 6 and table 3 below.

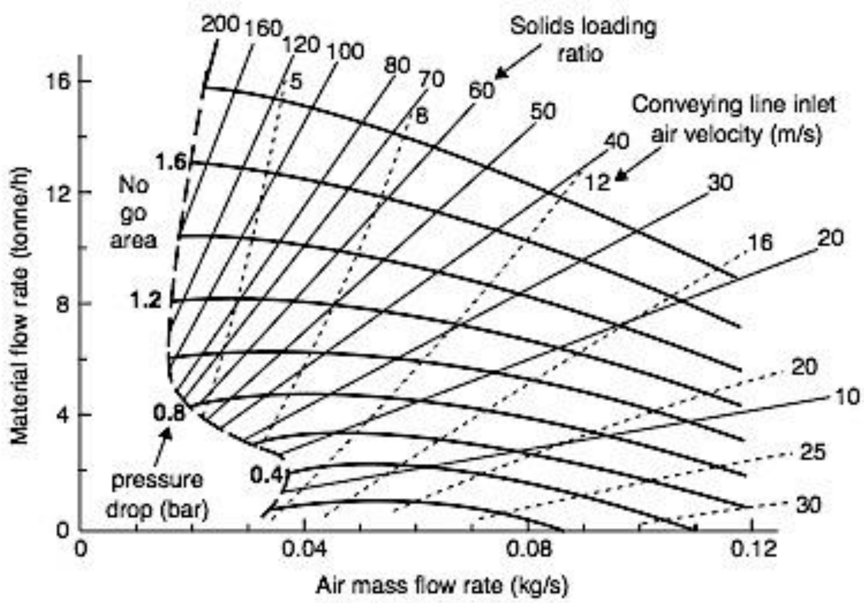

Figure 6: Portland Cement Conveying Characteristics in a 50 m Pipeline with 53mm Bore, and 9 Bends with D/d ratio of 24 [8]

Figure 6 represents existing conveying test data for Portland cement in a 50 m Pipeline with 53mm Bore, and 9 Bends with D/d ratio of 24. This initial data can then be scaled linearly to a longer length, the desired conveying length of the system, and the material mass flow rate and pressure drop can be reliably determined. Linear scaling is carried out via equation 13 below:

$$m_{p2} = m_{p1} * [\frac{L_2}{L_1}]^2. \quad (13)$$

The same procedure can be used to scale pipeline bore at given test data at desired conveying length [8].

The results of scaling analysis for Portland cement given the test data displayed in figure 6 above can be seen in table 3.

Table 3: Ordinary Portland Cement Scaled at 53 mm Bore from 50 m to 41 m

Air Mass Flow Rate (kg/s)	Conveying Line Pressure Drop (bar)	Initial Material Mass Flow Rate (tonne/h)	Initial Solids Loading Ratio	Scaled Material Mass Flow Rate (tonne/h)	Scaled Solids Loading Ratio	Volumetric Flow Rate of Air (m^3/s)	Supply Pressure (kN/m^2)	C1 (m/s)
0.02	1.8	16	200	19.51	271.00	0.0163	281.3	8.7
0.04	1.6	12.5	80	15.24	105.86	0.033	261.3	18.7
0.08	1.2	7	23	8.537	29.64	0.065	221.3	44.3
0.12	0.8	2	5	2.439	5.65	0.098	181.3	81.2

In figure 6, the maximum solids loading ratio for Portland cement is 200. The solids loading ratio of 271, highlighted in red in the table above, exceeds the maximum solids loading ratio of the established test data, which means that this system could not theoretically convey Portland cement successfully up to the associated material mass flow rate, 19.5 tonne/hr, and conveying line pressure drop, 1.8 bar. Theoretically the system could convey Portland cement with solids loading ratios spanning from 5.65 to 105.86. This implies both dilute and dense phase flow characteristics are achieved;

however, initial data had dilute flow phase characteristics with solids loading ratios that exceeded 15. This highlights the issue of definition in the field of pneumatic conveying, where dense phase flow is loosely defined as solids loading ratios exceeding 15, but in practice, bulk solids are conveyed in dilute phase at much higher solids loading ratios. Scaling of minimum air mass flow values at pressure drops allows for the identification of the conveying velocity limits of this scaled data, allowing the minimum conveying velocity for a material at a pressure drop to be identified [8]. This data for Portland cement is tabulated below.

Table 4: Minimum Conveying Velocity for Ordinary Portland Cement Scaling Results at 0.053 m Pipeline Bore

Conveying Line Pressure Drop (bar)	**C1 (m/s)**
0.20	35.38
0.40	32.10
0.60	22.80
0.80	13.53
1.00	9.14
1.20	8.31
1.40	9.65
1.60	9.38
1.80	10.90

Here, the minimum conveying velocities required at given system pressure drops for Portland cement are displayed.

This analysis assumes infinite available free air and allowable pressure drops in the system; however, in capability analysis, compressor capability and max safe system working pressure, including the working pressures of components, must be considered.

Compressor Analysis

The compressor available for this system is a fixed-speed rotary screw compressor. In a fixed-speed compressor, consistent voltage and frequency are always applied to the motor, which means that as air demand increases, system efficiency decreases. This system has air cooling and oil injection so that air entering the pneumatic conveying system will not be "hot" due to compression effects. The oil cools the air during compression and is filtered from the air before it enters the pneumatic conveying system. The effectiveness of this filter should be independently verified to ensure no oil enters the system. Figure 7 below is the manufacturer supplied Compressor Data Sheet.

KAESER COMPRESSORS

COMPRESSOR DATA SHEET

Rotary Compressor: Fixed Speed

MODEL DATA - FOR COMPRESSED AIR			
1	Manufacturer: **Kaeser Compressors, Inc.**		
2	Model Number: **SK 15 - 125 psig / 460V/3ph/60Hz**	Date:	**4/14/2016**
	[X] Air-cooled [ ] Water-cooled	Type:	**Screw**
	[X] Oil-injected [ ] Oil-free	# of Stages:	**1**
3*	Rated Capacity at Full Load Operating Pressure [a, e]	**71**	acfm [a,e]
4	Full Load Operating Pressure [b]	**115**	psig [b]
5	Maximum Full Flow Operating Pressure [c]	**125**	psig [c]
6	Drive Motor Nominal Rating	**15**	hp
7	Drive Motor Nominal Efficiency	**91**	percent
8	Fan Motor Nominal Rating (if applicable)	**--**	hp
9	Fan Motor Nominal Efficiency	**--**	percent
10*	Total Package Input Power at Zero Flow [e]	**4.0**	kW [e]
11	Total Package Input Power at Rated Capacity and Full Load Operating Pressure [d]	**13.9**	kW [d]
12*	Specific Package Input Power at Rated Capacity and Full Load Operating Pressure [e]	**19.58**	kW/100 cfm [e]

Figure 7: Kaeser Compressor Data Sheet [15]

According to manufacturer guidelines, this sheet gives the maximum available pressure at the maximum available volumetric flow fate in cubic feet per minute. These values are 125 psig (8.61 bar) and 71 cfm (0.0335 cubic meters per second). In scaling analysis, if maximum system demand exceeds these values the system is considered incapable of conveying at the described operational characteristics [16, 17, 18].

With compressor limitations accounted for, scaling analysis was carried out for all eight validation materials and is included in *Appendix 1.* The maximum system pressure drop for validation materials did not exceed that that the compressor could supply the associated volumetric flow output. For validation materials the maximum pressure drop in the system was 3.4 bar, the maximum system input pressure demand was 441 kN/m^2 , and the maximum required volumetric flow rate of air of a material was 0.098 cubic meters per minute at a conveying line pressure drop of 0.8 bar. As the fixed one stage compressor will be able to achieve greater volumetric flow rates at lower pressures the compressor should be suitable for all conveying conditions. Theoretical solids loading ratios exceeding solids loading ratios seen in experimental test data, is then the limiting factor on system capability, given this analysis [8].

System Component Selection and Validation

The components of the system can then be specified given known system conveying capability. Specified system component include a forward pressure vacuum displacement pump, feeding hopper, filter bag house, and rotary air lock feeder.

Vacuum Displacement Pump

The forward displacement vacuum pump chosen for this system is the 316-stainless steel threaded “Exair Line Vac”, displayed in figure 8 below.

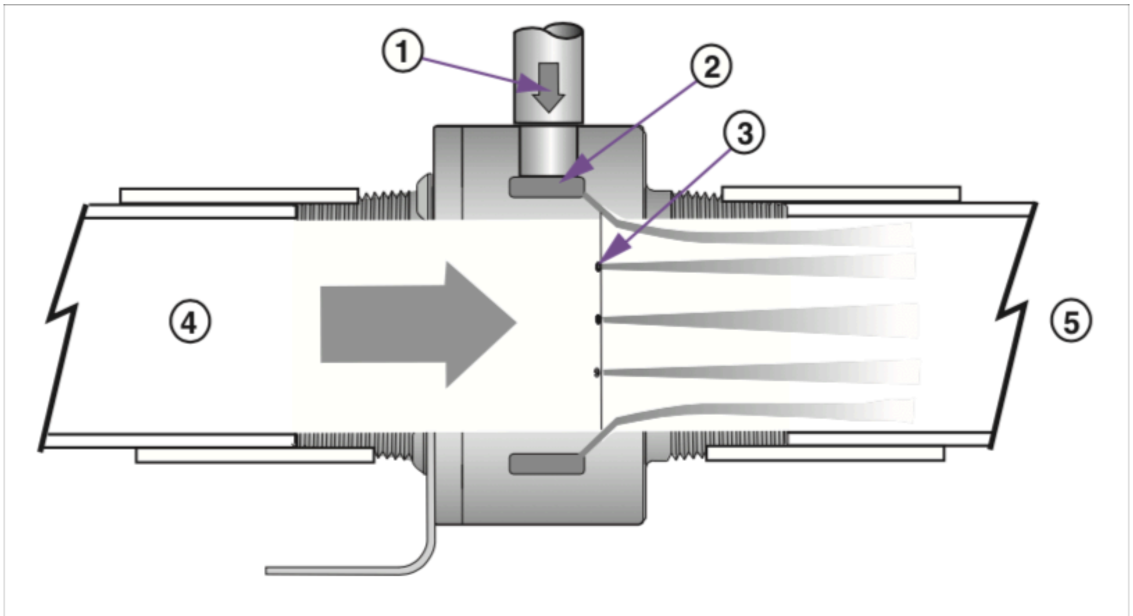

Figure 8: Forward Displacement Vacuum Pump [19]

This system attaches to the existing compressors through a compressed air line, denoted by (1) in figure 8 above, the compressed air then flows into an annular plenum chamber and is injected through directed nozzles into the throat. This creates a vacuum intake, denoted by (4), allowing for material to be drawn into the system. Air mass flow rate is controlled via an included pressure regulator. This system can be adjusted by manually increasing the size of the air injecting nozzles. The compressed air line for this system for conveying distances over 15.24 m should be 30 mm or larger The operating pressure range of this device is from 0.3-8.6 bar and thus falls within compressor capability [19]. This system can be threaded onto a pipeline for conveying and can be attached to a vacuum suction nozzle for feeding out of a bin, storage hopper, or silo [8].

Feeding System

For feeding in positive pressure systems a rotary air lock feeder has been selected, displayed in figure 9 below.

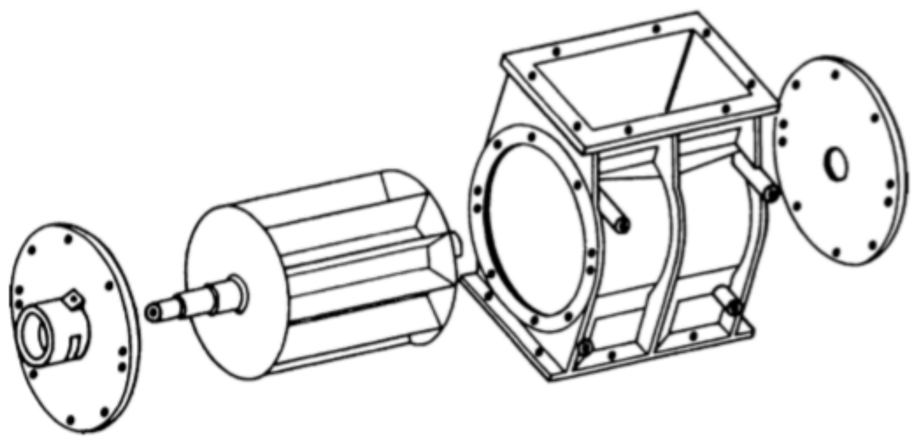

Figure 9: Rotary Air Lock Feeder [1]

This system consists of a rotor on a rotating shaft driven by a motor in a fixed body. A gravity fed hopper will be used. The rotational speed can be adjusted such that the filling efficiency of rotor pockets allows for desired mass flow rate to be achieved. As the rotor rotates, material in rotor pockets is discharged into the conveying line. The most common type of rotary valve is a drop through valve. Material from the supply hopper fills this type of rotor continuously. The sizing of this device depends on the volumetric capacity of the rotor and the outlet dimensions of the hopper to which the air lock attaches. The operational volumetric capacity of the device can experience changes due to pocket filling efficiency, which depends on the characteristics of the conveyed material, including density and cohesion. Additionally, system characteristics such a pressure differential across the feeder can reduce pocket filling efficiency. In sizing a device from a supplier, the required displacement of the material needs to be determined and is dependent on the desired system material mass flow rate and the density of the conveyed material. The required displacement can be then found by dividing the desired material mass flow rate by the density of the conveyed product. Maximum material mass flow rates from scaling analysis can then be used to determine the average, maximum, and minimum necessary displacement of this device [20]. These values allow for the specification of a feed system that will be able to convey a wide range of materials. These values are tabulated below.

Table 5: Material Flow Rates [20]

Material	Max Scaled Material Mass Flow Rate (tonne/hr)	Material Density (kg/m^3)	Displacement (m^3/hr)
Magnesium Sulphate	5	1380	3.62
Coal Pearls	2.52	690	3.65
Granulated Sugar (Fresh)	4.87	890	5.47
Flurospar	9.39	1580	5.94
Iron Powder	25.61	2380	10.76
Polyethylene Pellets	6.71	540	12.43
Ordinary Portland Cement	15.24	1070	14.24
Wheat Flour	20.73	510	40.65

From this analysis, it is seen that a rotary air lock with a displacement capability of 40.65 m^3/hr is necessary if this system was intended to convey this range of materials at these associated mass flow rates. If a rotary air lock with a lower displacement was selected, these materials could still be conveyed as long as the minimum conveying velocity of the material at that mass flow rate was met.

The number of blades the rotor should have can be assessed based on the pressure differential in the system. A ten-blade rotor is well suited for pressure differentials between 0.5 to 1.0 bar, an eight-blade rotor is well suited for pressure differentials from 0.2 to 0.5 bar, and a six-blade rotor is well suited applications were pressure differentials are less than 0.2 bar. As this system is intended to be highly versatile, a ten-blade device is specified. This may cause issues at lower pressure drops, which can be mitigated by reducing rotational speed [1].

Hopper

In specifying hoppers, hopper angle, minimum dimensions of hopper outlet, the ratio of material height to hopper width and safety features are considered. Additionally, the geometry of the feeding apparatus must be considered.

The hopper angle is the angle of the hopper wall measured from vertical. This angle determines how material will flow out of the hopper due to gravity [21]. Material flow out of hoppers is generally characterized as either funnel or mass flow. Funnel flow is characterized by flow in the middle of the hopper with areas of stagnation along the vessel wall whereas mass flow is characterized by uniform flow throughout the hopper [21]. Mass flow is ideal; however, headroom limitations factor into hopper choice. A greater amount of material can be stored in a wide hopper under funnel flow conditions, making it an attractive balance between headroom and material flow. To ensure desired material flow, the hopper angle must be specified. This angle is based on the material properties of the hopper wall and the conveyed material, specifically the angle of internal friction and wall friction angle. The angle of internal friction for a given wall and conveyed material is determined by testing methods described in ASTM D-6128. Because of this testing, shear stress values can be plotted against normal stress values. The angle of wall friction can then be determined graphically by drawing a line from the origin to the point on this line at which the wall material yields [21]. Design charts developed by *Jenike* can then be used to determine the appropriate hopper angle. For hoppers with a circular outlet, selected due to the application of a rotary air lock in this system, the design chart below (figure 10) is utilized. In selecting the hopper angle for a round circular outlet, industry best practice suggested the inclusion of a 3° margin of error.

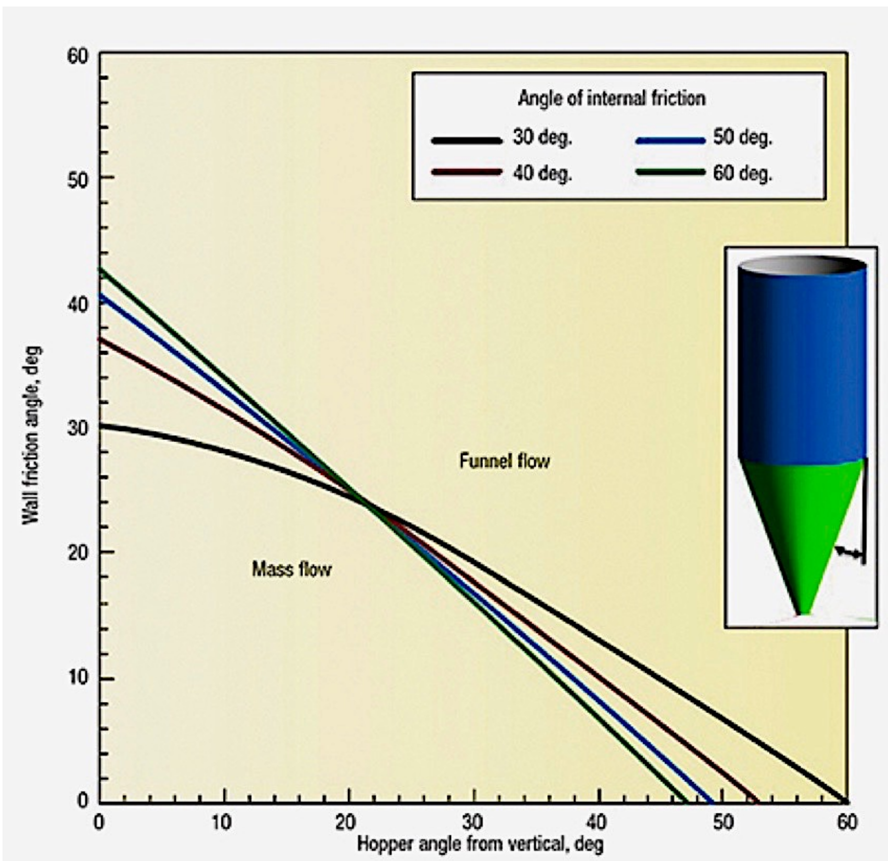

Figure 10: Hopper Angle for Round, Circular Outlet [21]

Given this figure, the appropriate hopper angle for a desired hopper material and conveyed material can be determined; however, because this system is intended to convey a wide range of materials, specifying a specific hopper angle based on feeding becomes challenging. This same challenge arises when specifying the minimum outlet dimensions of the hopper, which must be determined so that desired flow can be established. If the outlet is too small, undesirable flow characteristics can develop, which will eventually prevent flow. These characteristics commonly include arch formation *(seen below in figure 11)*, a situation in which the material is packed onto itself and creates an arch which prevents flow, and rat-holing *(seen below in figure 11)*, a situation in which material is packed towards the vertical walls of the hopper into two stagnant regions resulting in a no-flow situation. The required minimum outlet diameter is then dependent on the conveyed materials bulk density and cohesive strength. In hoppers with circular outlets, an outlet diameter that prevents rat-holing also inherently prevents arch formation.

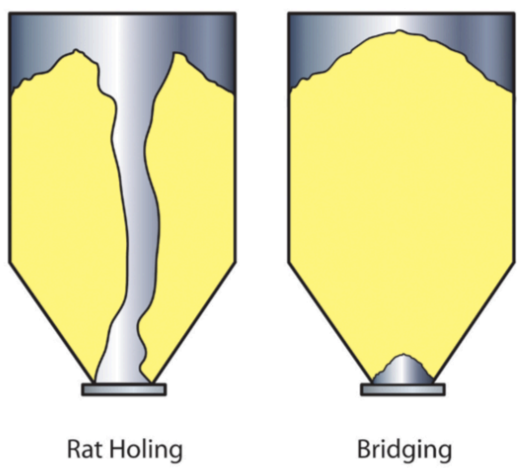

Figure 11: Undesirable Hopper Flow Characteristics [22]

Wall friction testing is the only way to reliably determine appropriate hopper angle and outlet; however, in specifying a hopper that will adequately conveyed a wide range of material, selection of a 60° hopper angle is sufficient [24]. This angle is selected because it is a standard hopper angle for funnel-flow silos. This angle allows for easy manufacturing as it leads to minimal waste generation [24]. To ensure proper operation over a range of materials, air discharge aids must be installed in the hopper. These work by dilating the conveyed material to increase flow capability by reducing its yield strength, by reducing friction between particles, by reducing particle adhesion, or by changing the flow regime through affecting the solids loading ratio at and around the hopper outlet. In this design, fluidizing pads will be installed in the hopper. These devices dilate the material, causing increased separation between particles. This method is suitable for particles with average particle diameters of less than 75 micrometers (or where at least 25% of the material exhibits particle diameters of less than 75 micrometers). Air is injected during discharge, reducing the materials bulk strength and friction between particles and the wall at the hopper outlet. These pads can be mounted on existing hoppers. They use layered mesh to distribute air by maintaining a pressure differential across the mesh. Air consumption of these devices is generally 8.5 m^3/min for every meter of aeration pad. These devices would not always be in use but rather implemented when hopper discharge issues arose [23].

Issues stemming from the use of aeration pads include increased material segregation, increased friable material attrition and an increased likelihood of fine creation in the conveying of plastics. Additionally, air provided to fluidization pads must be free of oil and excessive moisture such that the material is not contaminated in the hopper [23].

Filters

Generally, filters are constructed out of a wire cage in which a filter material "envelope bag" is placed. This construction allows for the filter to be sealed to the chamber through which the system exhausts. Air with entrained particles moves through the wire cage and contacts the filter. Cleaned air then moves through the filter and is exhausted. These systems are designed such that filters can be assessed without dissembling the filter chamber.

Filters are sized in terms of gas to cloth ratio. This is based on the flow of gas through a unit area of filter cloth. This develops a drop in pressure. If this pressure falls within system limits, then the system is capable of conveying under those conditions. This ratio is expressed as

$$\gamma^* = \frac{\dot{V}}{A_F} \qquad (14)$$

where A_F is the area of the filter in m^2 and $\dot{V}$ is the volumetric flow rate of air in m^3/min. This value is ultimately dependent on characteristics of the particle, specifically particle average diameter. Typical gas cloth ratios for validation materials are shown below in table 6. These values can then be used to determine necessary filter size for a given filter material type and filter cleaning system [1]. Values at maximum air volumetric flow rates determined via scaling were found. These values, in units of ft^2/min per ft^2 of cloth (provided by the Environmental Protection Agency) are below [25].

Table 6: Filter Selection[25]

Validation Material	Typical Gas/Cloth Ratio for Reverse Air/ Woven Fabric	Typical Gas/Cloth Ratio for Reverse Air/ Felt Fabric	Maximum Volumetric Flow Rate from Scaling (ft^3/min)	Theoretical Necessary Filter Area Woven (ft^2)	Theoretical Necessary Filter Area Felt (ft^2)
Ordinary Portland Cement	2	8	69.92304	34.96152	8.74038
Granulated Sugar (Fresh)	2	13	69.92304	34.96152	5.378695385
Iron Powder	3	11	69.92304	23.30768	6.35664
Polyethylene Pellets	2.5	7	69.92304	27.969216	9.989005714
Wheat Flour	3	12	69.92304	23.30768	5.82692
Coal Pearls	2.5	8	69.92304	27.969216	8.74038

A filter bag house system can then be specified with interchangeable filters, which allow for the adjustment of gas cloth ratio for system optimization. Different types of cloth can be used depending on the tested material. Additionally, a cleaning scheme for filter cleaning must be addressed. The most common type of filter cleaning in pneumatic conveying is a reverse jet cleaning system. In these systems, air jets are placed at the mouth of the filter bag supported by the filter supports. From these nozzles, high-pressure air can be directed into the bag, causing particles to dislodge from the filter. The source of this air is typically independent from the system source [1].

System Design Summary

The system then is theoretically capable of conveying the eight validation materials over a wide range of material mass flow rates and conveying line pressure drops, these analyses can be seen in *Appendix 1*. The selected system pipeline bore and equivalent conveying length to allow for a range of materials to be conveyed is 53 mm and 41 m respectively. The one stage fixed speed rotary air compressor to which the system was designed was deemed sufficient and a simple positive displacement vacuum device that this compressor could support was specified. Additional system components that were specified include a hopper with an angle of 60° and fluidization pads, a rotary air lock feeder for positive pressure conveying with a maximum necessary displacement capability of 40.65 cubic meters per hour, and theoretical necessary filter sizes for validation materials at maximum volumetric flow rates.

Instrumentation

Instrumentation allows for data collection of velocity of particles in flow, the pressure differential across the system, and the mass flow rate of air and material through the system. The collection of this data allows for the change in material properties as well as system damage due to conveying to be analyzed. Once material is added to the system, invasive measurement techniques are no longer preferable as they can affect system conveying characteristics and instruments are easily damaged in gas solid flows.

Instrumentation applied to this system includes a laser Doppler velocimeter, which allows for particle velocities to be determined, a sight glass, which allows for flow phase to be determined, a pressure transducer, which allows for pressure changes in the system to be determined, a Coulombmeter, which allows for electrostatic charge build up in a system test section to be determined, and a hot wire anemometer, which allows for the velocity of air in the system to be measured before the introduction of conveyed material.

Laser Doppler Velocimeter

A laser Doppler velocimeter, pictured in figure 12 below, measures instantaneous particle velocity with using a monochromatic laser. The laser reflects off the particles and is measured by a light detector. The Doppler effect states that the changes in the wavelength of reflected radiation are a function of the objects relative velocity [26]. The objects relative velocity can then be determined by measuring changes in the reflected laser light, by superimposing the original and reflected signals. This device then can be used to determine the relative velocity of particles in flow, without disrupting the flow. The velocity of particles in the flow then allows for the identification of the minimum conveying velocity of materials and for information regarding how fast particles are traveling during collisions to be derived [26].

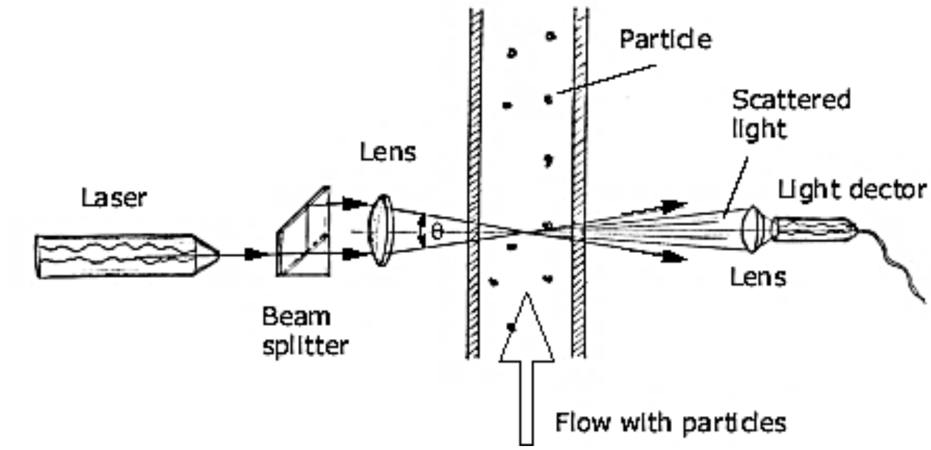

Figure 12: Laser Doppler Velocimeter [27]

Sight Glass

A sight glass, pictured in figure 13 below, is used in this system to visually inspect flow characteristics of the entrained particles. This will allow for the identification of the minimum conveying velocity and the flow phase. Sight glasses are regularly used in pneumatic conveying test loops as flow phase and flow characteristics, such as plug flow or bed formation are challenging to characterize without visual inspection. Using a sight glass, characteristics of flow, as well as the conveying air velocity at which dilute flow occurs, can be determined. These devices are made out of borosilicate glass or polycarbonate. Borosilicate glass is more suited to abrasive material conveying and a highly resistant to thermal shock and is therefore the preferred material for this system. They are generally available at lengths around 200 mm. They are connected to the system via air tight flanges with gaskets, which suppliers work with customers to develop. They experience wear faster than conveying line materials and are intended to be replaced at intervals. By nature of flanged connections and material, there is a negligible change to the overall system pressure drop [28].

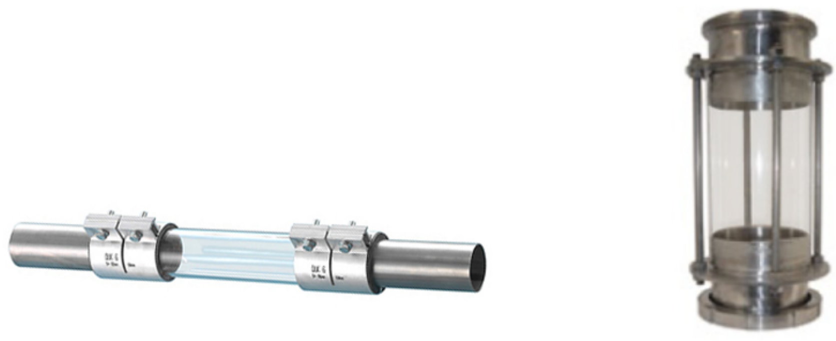

Figure 13: Sight Glass Tubes [28,29]

Pressure Transducer

Flow characteristics can be determined by examining pressure differentials in the system. Depending on the application of instrumentation, changes in near instantaneous pressure readings can indicate blockages in the system or areas where flow becomes dense. This can be achieved by utilizing a pressure transducer, displayed in figure 14 below, which is directly applied to the conveying line. Pressure transducers use strain gages to find system pressure.

Several types of transducers exist. Most commonly, they consist of a diaphragm, which deforms with pressure, and a transducer, which converts this pressure into an electrical signal. Transducers applied to lines must be sealed so that the conveyed material does not damage the instrument. A common way to do this would be to use a pressure transducer with a diaphragm seal. These devices work by utilizing a column of water, which is capped with sensitive metal plates. When pressure is applied to these plates, they transmit pressure via the water column to another diaphragm, which acts on an air column, which in turn acts on the transducers surface [1]. Transducers will be used at the inlet and outlet of the system as well as where the system transitions from horizontal to vertical conveying, allowing total system pressure drop, as well as the contribution to pressure drop caused by changes in conveying direction, and therefore inherent deceleration of conveyed particles, to be determined.

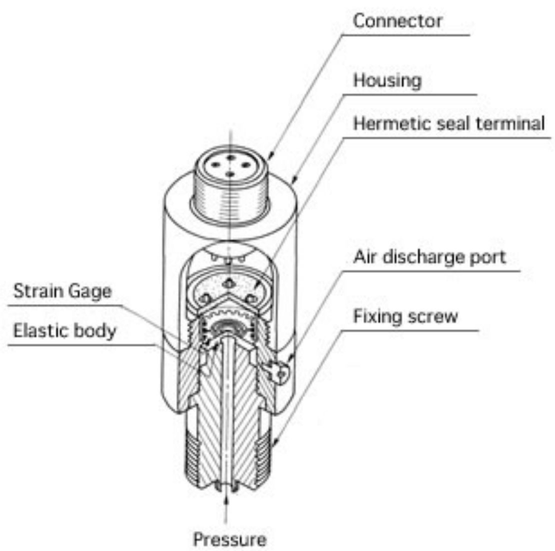

Figure 14: Pressure Transducer [31]

Coulombmeter

Combustion of powders and dust in pneumatic conveying is common. Many of these events occur because of static electric build-up of powders during conveying, which can cause spark discharge. For this reason, an experimental setup for measuring static electric charge build-up of powders is included in this system. This experimental set up was developed in a paper entitled *"Measurement of Electrostatic charging during the conveying of powders"* published in the *Journal of Loss Prevention in Process Industries* in 2017 [32]. This setup allows for the measurement of the static electric charge build-up of powders in a section of the system by grounding the surrounding system components and surrounding the charge measurement section with a Faraday cage. This system calls for the application of a coulombmeter, which measures the electric charge of particles. This could theoretically be implemented in the system by grounding all but a test section; however, for reliable data to be gathered, precise system control is necessary. To determine static electric build-up of particles during conveying, this system could instead be built independently. It could utilize the test loop's prime mover and feeding device which could be detached via flanged connection and attached to this test system, making capital cost of this system low. A schematic of this system is pictured in figure 15 below where W is an air velocity measurement device, E is an electric field strength meter and Q is a coulombmeter [32].

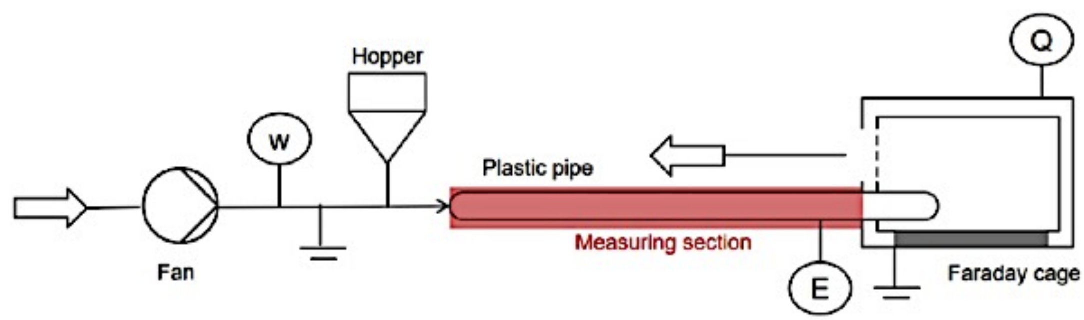

Figure 15: Test Apparatus that Measures Static Electric Build-up [32]

Hot Wire Anemometer

An important material conveying characteristic is minimum conveying velocity. This is the minimum air velocity needed to produce specified conveying characteristics. A hot wire anemometer can be used to measure air velocity before the addition of solids to the system conveying line. This will allow the air velocity, and therefore mass flow rate, in the system to be determined when conveyed materials reach desired flow characteristics.

To measure air velocity, a hot wire anemometer, displayed below, is exposed to the air and the heat convected is measured. This reading can then be used to determine air velocity as there is a change in electric current in the wire to maintain constant temperature. The charge is directly proportional to air velocity [33, 34].

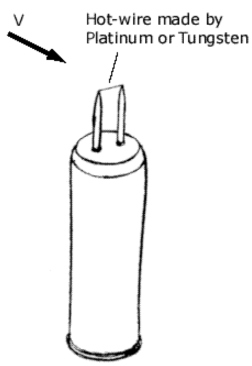

Figure 16: Hot Wire Anemometer [33]

Testing Standards

To interpret data gathered from these devices, existing test standards must be identified. These standards will be used to help theoretically validate this test system design. Pneumatic conveying suffers as a field from a lack of standards that clearly define characteristics such as flow and phase systems. However, some existing testing standards allow for clear communication between testing groups and industrial clients. In this section, instrumentation and associated test standards regarding the abrasion of the system by the material, the abrasion of the material by the system, material friability or particle attrition, flow rate of the material in the system, and flow characteristics throughout the system are explored [1].

System wear caused by material abrasion is common when highly abrasive materials like sand are conveyed. Abrasion is defined by the Society of Automotive Engineers as the removal of material by the mechanical action of “hard” particles with a material surface [9]. System abrasion is a concern as wear over time leads to lower system lifespan. Elbows or bends are particularly susceptible to wear as changes in flow direction can cause direct impacts between the conveying line and the conveyed particles. Elbows wear out on average ten times as fast as straight conveying line sections [11]. Abrasive properties of commonly conveyed materials and common pipeline materials are well known due to laboratory testing. In general, material wear abrasion testers, in which disks of the test material are spun via a turntable and abraded by disks to which particles are bound for a number of cycles at a given load, are used. Here the amount of abrasion is quantified by the change of the haze of the material. This process is defined by *ASTM G65-04 Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus* [10]. A more common way to quantify the effect of a particles abrasion on a material is to examine the mass change in the test specimen against the number of abrasion cycles. In the field of pneumatic conveying, no standards regarding system wear exist. Analysis of various materials for proposed system is usually carried out independently. In this analysis, changes in material surface characteristics are examined via visual inspection and microscopy of various types [1]. These changes are then analyzed and material specific standards are determined. Similarly, materials intended for conveying with corrosive properties are tested in a laboratory setting to determine appropriate conveying line material selection. In some cases, to allow for visual inspection a section of the conveying line is made removable via a bolting system.

Friable materials are materials that break down into smaller units when contacted by surfaces. This same property is referred to as particle attrition [1,8]. Material friability is a chief concern in pneumatic conveyance as friable materials may experience reduced average diameter after conveying due to impacts between material and the conveying line. This can lead to dust creation, processing problems, and the increased range of particle size can cause greater segregation of the material. One way to test a conveyed materials friability or tendency toward particle attrition is to convey the testing material at various gas velocities and then compare the particle exit condition to particle input conditions. The change in particle diameter can be quantified by sieving processes, which can quantify by mass the number of particles under the lower original diameter limit [1]. Other methods for examining material friability include the examination of particles before and after conveying is via microscopy or x-ray diffraction [1].

In using these methods to quantify material friability, samples must be removed from the system for testing [1]. In order for samples to be removed during processing, diverter valves and air locks must be installed that allow for a metered amount of conveyed material to be removed at a point in the processing. These diverters can be installed at the receiving hopper. Collected samples can then be tested for various property changes.

The material transport rate of the system is the mass of conveyed material over time. In measuring this, it is important that unobtrusive instrumentation is used such that the flow is not disturbed. This property is most simply measured by massing the input and output of conveyed material over time. This can be achieved by instrumenting the system with controlled feeding and load cells on the receiving hopper, silo or bin. These load cells are then utilized to monitor the mass that has passed through the system over time [1,8].

The goal of determining flow characteristics throughout the system is to determine the phase in which the material is being conveyed. It is important to identify the desired conveying phase of a system and then monitor the system during testing to verify these design criteria are meet. Some tests regarding flow phase can be based on the mass flow ratio (the ratio of the mass flow rate of the conveyed solid (m_p) to the mass flow rate of the conveying air (m_a)). In a general sense, dilute phase systems have mass flow ratios of 0 to 15 and systems with mass flow ratios of 15 or above are dense phase. These definitions act as general guidelines. Via sight glasses, visual inspection is used to identify flow phase via the use of clear conveying lines sections, this design can be seen below in figure 17 [12].

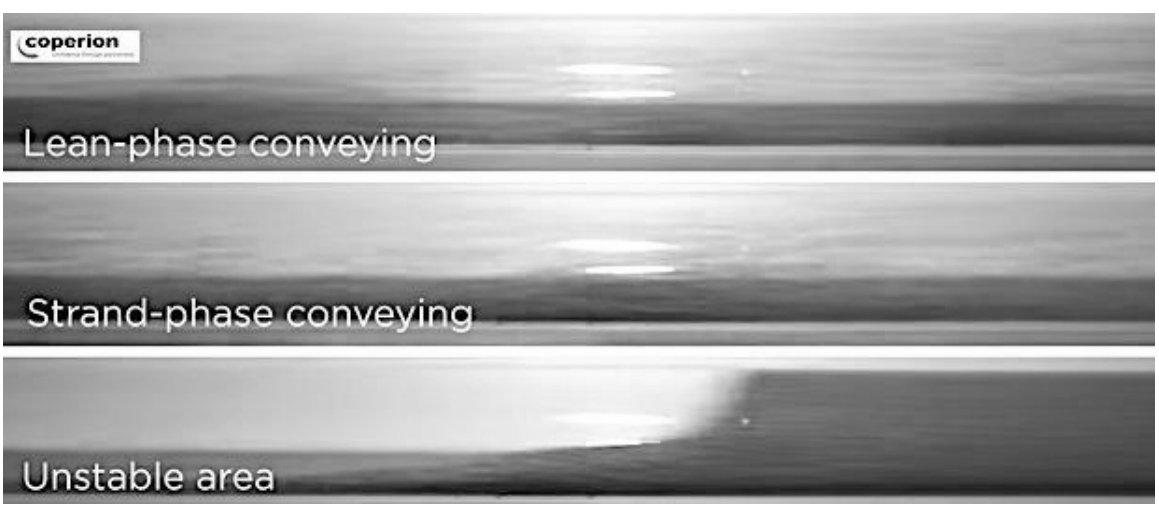

Figure 17: Flow characteristic identification via visual inspection in clear conveying

lines [12]

Here, the application of a clear conveying line section, accompanied by pressure data and potentially high-speed camera recording, allows for the visual identification or verification of flow phase as well as flow characteristics such as bed formation and plugs [12,1].

Design Drawings with Instrumentation

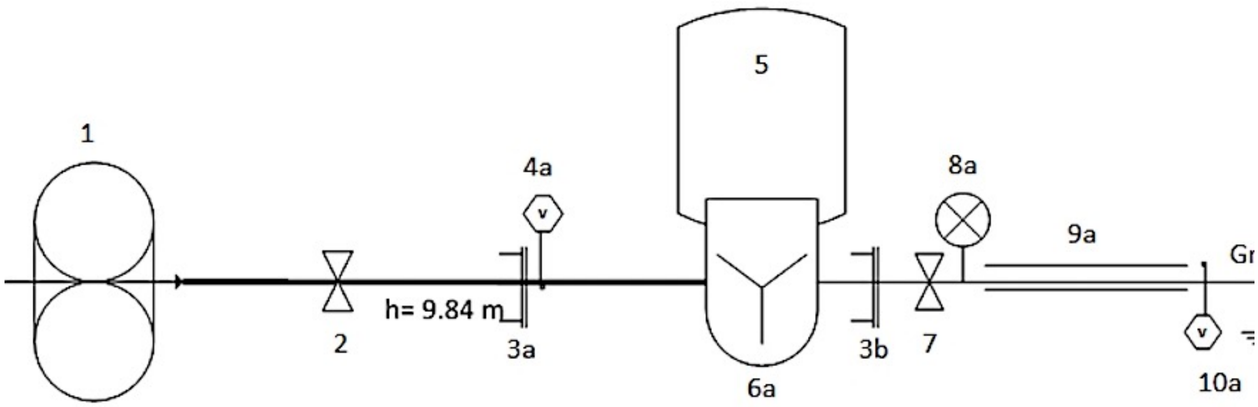

Figure 18: Prime Mover and Feeding Device

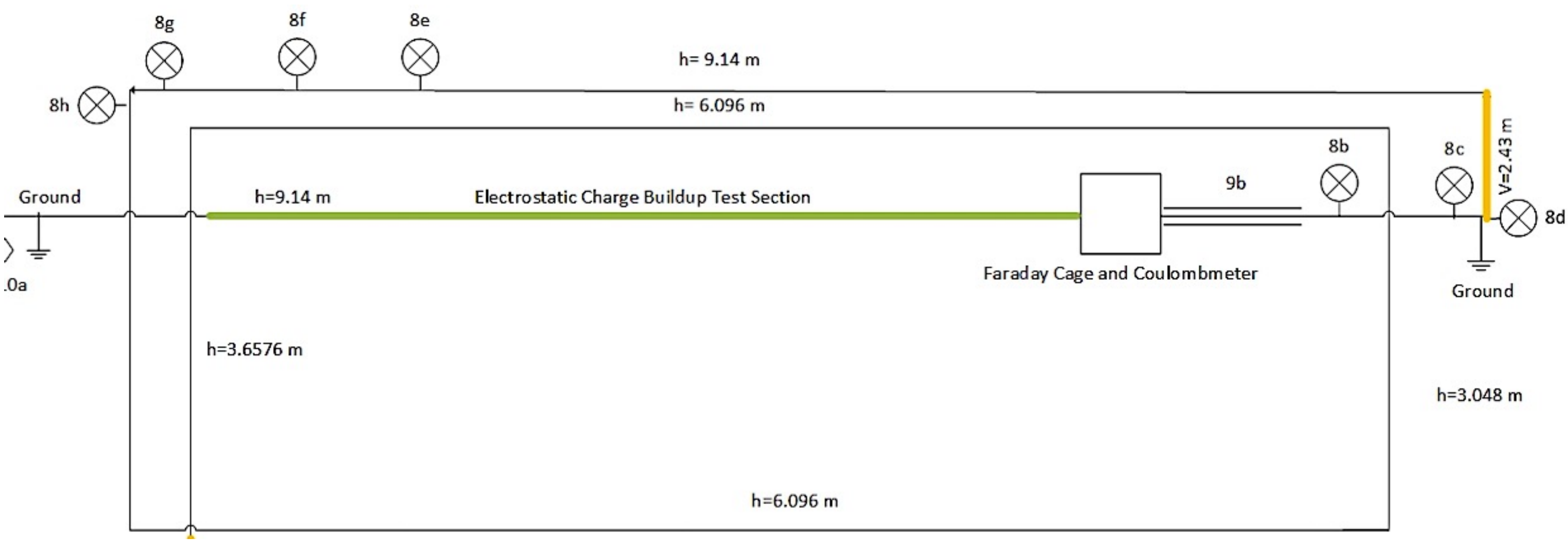

Figure 19: Pipeline

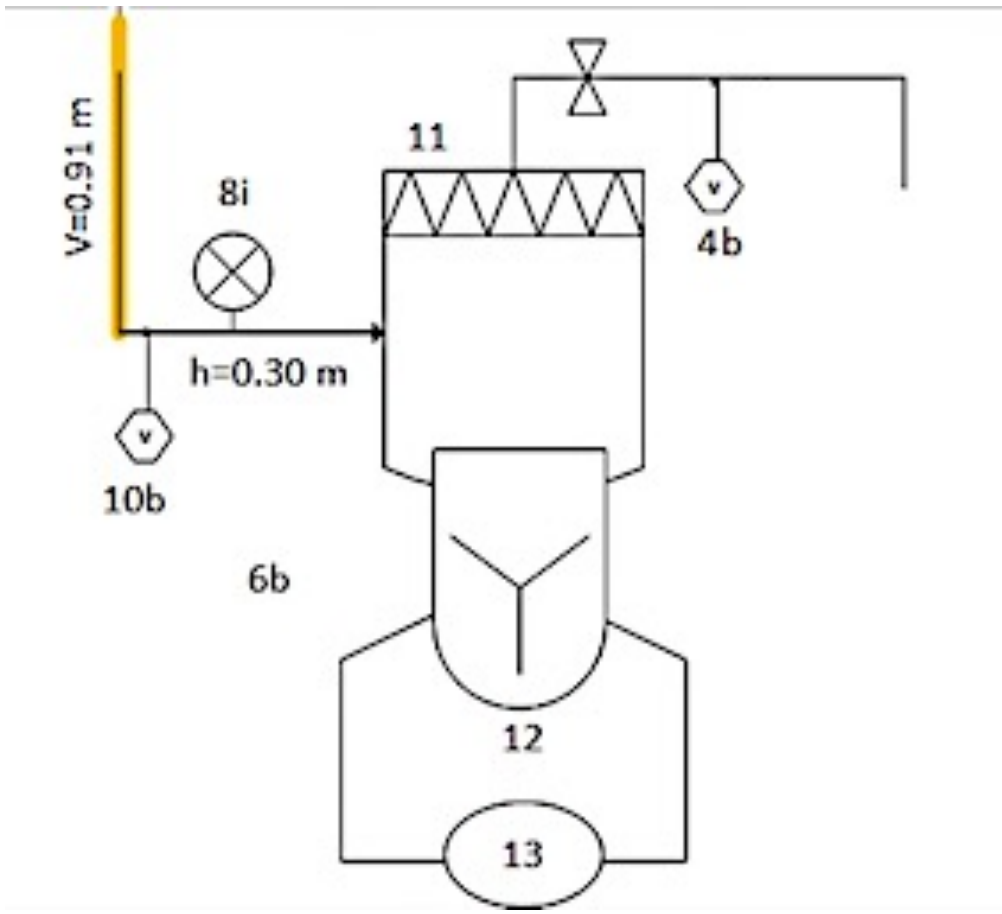

Figure 20: Material Separation and Exhaust

Design Components from System Drawing

1 Rotary Screw Compressor

2 High Pressure Valve

3a and 3b Potential Flanged Connections

4a and 4b Hot Wire Anemometers

5 Storage Hopper

6a and 6b Rotary Air Lock Feeders

7 High Pressure Valve

8a through 8i Pressure Transducers

9a and 9b Sight Glasses

10a and 10b Laser Doppler Velocimters

11 Filter (Materials Separation)

12 Conveyed Material Storage

13 Load Cell

In this design pressure transducers (8a through 8i) are placed leading up to in horizontal conveying, before and after elbows that converts flow from vertical to horizontal and horizontal-to-horizontal to experimentally determine pressure losses due to the changes in acceleration of the solid gas flow in bends. Additionally, pressure transducers are placed at the inlet and outlet of the system to allow for experimental pressure drop to be determined. A 200m long sight tube (9a) was placed 600 mm after the introduction of solids into the system to allow flow phase after material entrainment to visually assessed. An additional sight tube (9b) was placed near the end of the first long conveying section approximately 8.3 meters after solids were added to the system to allow material flow characteristics to be visually assessed. Laser Doppler velocimeters were placed directly after the sight tube, near the solids introduction point (10a) , to determine particle velocity after entrainment, and near the outlet of the system to determine outlet particle velocity (10 b). Finally hot wire anemometers were placed directly before solids were introduced to the system and directly after solids were filtered from the system to determine conveying air velocity at the inlet and the outlet of the system (4a and 4b). A storage hopper (5) feed the system via rotary air lock (6a), material was also metered out of the system into a storage silo (12) via a rotary air lock (6b). High pressure safety valves were placed before an after solids introduction in case pressures surges due to solids introduction occur (2 and 7). The systems prime mover is rotary screw compressor (1). Potential flanged connections (3a and 3b) could be incorporated into system design to allow for system conversion to negative pressure via the Line Vac vacuum pump discussed in system components. These connections would have associated pressure loss and wear more quickly then the conveying line. A filter bag is for materials separation is incorporated in system design (11). Finally, a load cell 9130 is placed under the discharge silo (12). If the material feed rate and metering out of this system are know the mass of material discharged over time can be used to roughly approximate the material mass flow rate in the system. The electrostatic charge measurement device described in the instrumentation section is pictured in figure 19. In these V refers to vertical conveying sections and h refers to horizontal conveying sections.

Conclusions

A design for a system that is capable of conveying a wide range of materials defined by eight validation materials, ordinary Portland Cement, Granulated Sugar (Fresh), Magnesium Sulphate, Iron Powder, Fluorspar, Polyethylene Pellets, Wheat Flour and Coal Pearls, was specified in terms of system geometry, prime mover, hopper angle, rotary airlock displacement capability, and material specific filter sizing. The selected system pipeline bore and geometry to allow for a range of materials to be conveyed is a 53 mm bore and a pipeline with a horizontal conveying distance of 33.83 m, a vertical conveying distance of 2.438 m with 8 long radii 90° elbows. Geometry was limited by installation site architecture. The number of bends was selected such that the effect of bends and specifically of converting flow from vertical to horizontal and horizontal-to-horizontal could be studied. This selection is also reflective of existing test system designs which employed numerous elbows. The one stage fixed speed rotary air compressor to which the system was designed was deemed sufficient and a simple positive displacement vacuum device that this compressor could support was specified. A specific hopper angle could not be designed towards material characteristics, therefore, a standard hopper angle of 60° was selected. This angle is commonly manufactured and represents an economic choice. To ensure proper discharge of multiple materials fluidization pads should be installed in this device. A rotary air lock feeder for positive pressure conveying was investigated. In specifying rotary airlocks positive displacement capability to ensure a material mass flow rate is determined the max displacement this device would require to meet conveying requirements of the validated materials is 40.65 cubic meters per hour, Finally the application of filters in materials separation was explored and theoretical necessary filter sizes for validation materials at maximum volumetric flow rates were calculated.

The eight validation powders were selected as they represent a wide range of material properties and conveying characteristics with mean particle size ranging from 14 to 10000 micrometers, a bulk density ranging from 690 to 1070 kg/m3, and material permeability ranging from 0.34 to 420 m3s/kg*10-6. Due to these properties this range of materials displayed both dilute and dense flow phase characteristics at minimum conveying velocities ranging from 3 m/s to 16 m/s.

Finally a set of instruments was selected that will allow for data regarding the velocity of particles in flow, the pressure differential across the system, and the mass flow rate of air and material through the system to be collected. This will allow the user to develop protocol such that the change in material properties as well as system damage due to conveying can be analyzed. Instrumentation applied to this system includes a laser Doppler velocimeter, which allows for particle velocities to be determined, a sight glass, which allows for flow phase to be determined, a pressure transducer, which allows for pressure changes in the system to be determined, a Coulombmeter, which allows for electrostatic charge build up in a system test section to be determined, a hot wire anemometer, which allows for the velocity of air in the system to be measured before the introduction of conveyed material and a load cell which allows for the quantification of discharged material mass .

Recommendations for Further Work

Future design work should consider carefully system safety requirements regarding pressure in the system and powder control to prevent combustion via valves and venting. Additionally, moisture in the system changes conveying characteristics drastically and should be considered in further work. The next step in this process is to communicate with the client regarding project budget and reach out to pneumatic conveying suppliers whose product specific data is critical in the design of this unique system.

Appendix

Appendix 1: Material Conveying Characteristics and Scaling Analysis

- All Conveying Data included in Appendix One is sourced from

[13] Mills, David. “Appendix 1: Determination of Relevant Material Properties.” *Pneumatic Conveying Design Guide*, 2nd ed., Elsevier Butterworth-Heinemann, 2004, pp. 595–616.

* Note in scaled data tables highlight scaled solids loading ratios exceed ratios seen in actual test data

Ordinary Portland Cement: Conveying Characteristics and Scaling Analysis

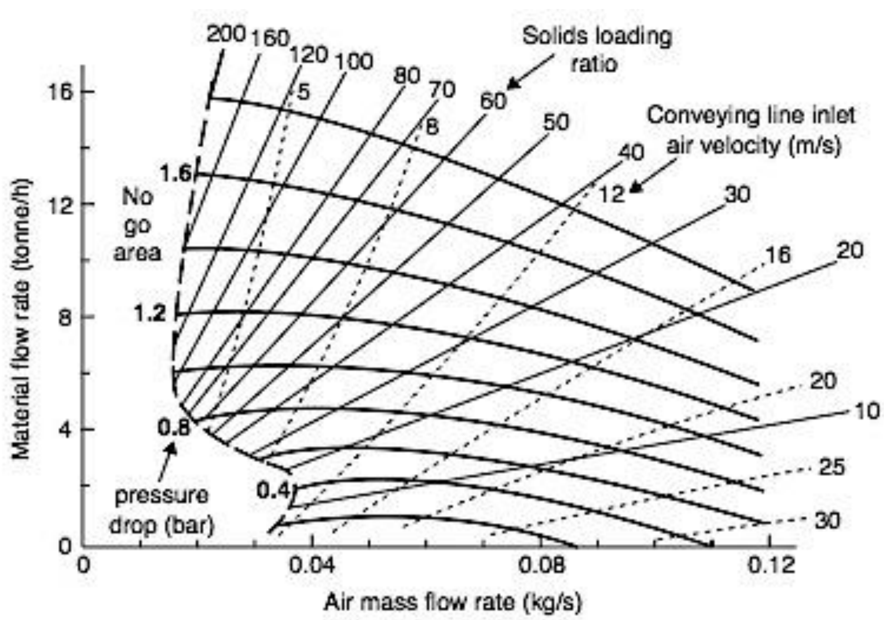

Figure A1.1: Portland Cement Conveying Characteristics in a 50 m Pipeline with 53mm Bore, and 9 Bends with D/d ratio of 24

Scaling Analysis:

Ordinary Portland Cement	Initial Conveying Length (m)	50	Scaled Conveying Length (m)	41				
Air Mass Flow Rate (kg/s)	Conveying Line Pressure Drop (bar)	Initial Material Mass Flow Rate (tonne/h)	Initial Solids Loading Ratio	Scaled Material Mass Flow Rate (tonne/h)	Scaled Solids Loading Ratio	Volumetric Flow Rate of Air (m^3/s)	Supply Pressure (kN/m^)	Conveying Velocity C1 (m/s)
0.02	1.80	16.00	200.00	19.51	271.00	0.016	281.3	8.72
0.04	1.6	12.5	80	15.24	105.86	0.033	261.3	18.77
0.08	1.2	7	23	8.54	29.64	0.065	221.3	44.32
0.12	0.8	2	5	2.44	5.65	0.098	181.3	81.15

Table A.1: Scaled Conveying Characteristics Ordinary Portland Cement Scaling Results at 0.053 m pipeline bore

Scaled Minimum Conveying Limits Ordinary Portland Cement	
Conveying Line Pressure Drop (bar)	**C1 (m/s)**
0.20	35.38
0.40	32.10
0.60	22.80
0.80	13.53
1.00	9.14
1.20	8.31
1.40	9.65
1.60	9.38
1.80	10.90

Table A.2: Minimum Conveying Velocity Ordinary Portland Cement Scaling Results at 0.053 m pipeline bore

Granulated Sugar Fresh: Conveying Characteristics and Scaling Analysis

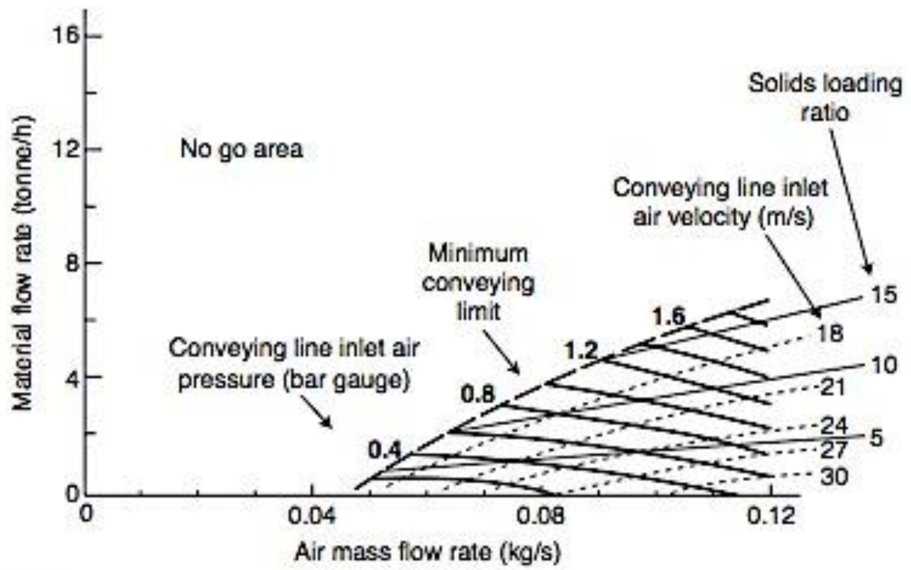

Figure A1.2: Fresh Granulates Sugar Conveying Characteristics in a 50 m Pipeline with 53mm Bore, and 9 Bends with D/d ratio of 24

Scaling Analysis:

Granulated Sugar (Fresh)	Initial Conveying Length (m)	50	Scaled Conveying Length	41				
Air Mass Flow Rate (kg/s)	Conveying Line Pressure Drop (bar)	Initial Materia l Mass Flow Rate (tonne/ h)	Initial Solids Loading Ratio	Scaled Material Mass Flow Rate (tonne/h)	Scaled Solids Loading Ratio	Volumetric Flow Rate of Air (m^3/s)	Supply Pressure (kN/m^)	Conveying Velocity C1 (m/s)
0.06	0.40	1.50	7.80	1.83	8.47	0.04896	141.3	52.06
0.08	0.8	3	10	3.66	12.70	0.06528	181.3	54.10
0.1	1.2	4	12.1	4.88	13.55	0.0816	221.3	55.40
0.12	1.8	6	16	7.32	16.94	0.09792	281.3	52.30

Table A.3: Scaled Conveying Characteristics Granulates Fresh Sugar Scaling Results at 0.053 m pipeline bore

Magnesium Sulphate: Conveying Characteristics and Scaling Analysis

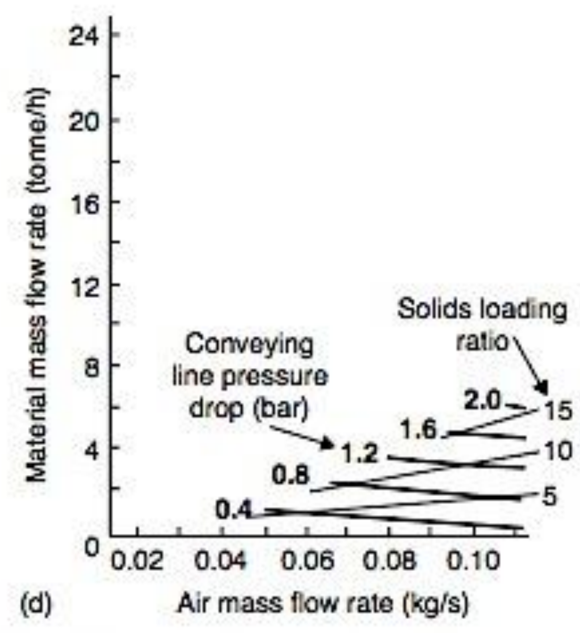

Figure A1.3: Magnesium Sulphate Conveying Characteristics in a 50 m Pipeline with 53mm Bore, and 9 Bends with D/d ratio of 24

Magnesium Sulphate	Initial Conveying Length (m)	50	Scaled Conveying Length	41				
Air Mass Flow Rate (kg/s)	Conveying Line Pressure Drop (bar)	Initial Material Mass Flow Rate (tonne/h)	Initial Solids Loading Ratio	Scaled Material Mass Flow Rate (tonne/h)	Scaled Solids Loading Ratio	Volumetric Flow Rate of Air (m^3/s)	Supply Pressure (kN/m^2)	Conveying Velocity C1 (m/s)
0.07	0.40	1	4.00	1.22	4.84	0.05712	141.3	60.74
0.08	0.8	2	7.5	2.44	8.47	0.06528	181.3	54.10
0.09	1.2	3	11.5	3.66	11.29	0.07344	221.3	49.86
0.1	1.55	4.1	14	5.00	13.89	0.0816	256.3	47.84

Table A.4: Scaled Conveying Characteristics Magnesium Sulphate Scaling Results at 0.053 m pipeline bore

Iron Powder: Conveying Characteristics and Scaling Analysis

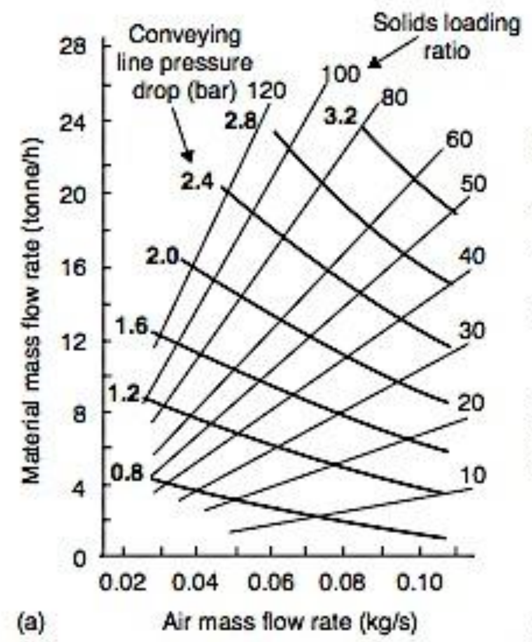

Figure A1.4: Iron Powder Conveying Characteristics in a 50 m Pipeline with 53mm Bore, and 9 Bends with D/d ratio of 24

Iron Powder	Initial Conveying Length (m)	50	Scaled Conveying Length	41				
Air Mass Flow Rate (kg/s)	Conveying Line Pressure Drop (bar)	Initial Material Mass Flow Rate (tonne/h)	Initial Solids Loading Ratio	Scaled Material Mass Flow Rate (tonne/h)	Scaled Solids Loading Ratio	Volumetric Flow Rate of Air (m^3/s)	Supply Pressure (kN/m^2)	Conveying Velocity C1 (m/s)
0.04	0.80	3.95	30.00	4.82	33.45	0.03264	181.3	27.05
0.06	1.2	6.1	30	7.44	34.44	0.04896	221.3	33.24
0.08	2	11	40	13.41	46.58	0.06528	301.3	32.55
0.1	3.2	21	60	25.61	71.14	0.0816	421.3	29.10

Table A1.5: Scaled Conveying Characteristics Iron Powder Scaling Results at 0.053 m pipeline bore

Flurospar: Conveying Characteristics and Scaling Analysis

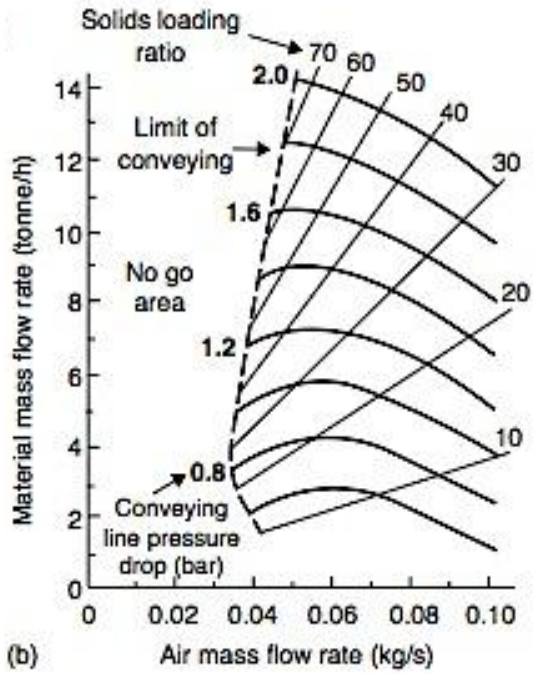

Figure A1.5: Flurospar Conveying Characteristics in a 70 m Pipeline with 53mm Bore, and 9 Bends with various D/d ratios

Flurospar	Initial Conveying Length (m)	70	Scaled Conveying Length	41				
Air Mass Flow Rate (kg/s)	Conveying Line Pressure Drop (bar)	Initial Material Mass Flow Rate (tonne/h)	Initial Solids Loading Ratio	Scaled Material Mass Flow Rate (tonne/h)	Scaled Solids Loading Ratio	Volumetric Flow Rate of Air (m^3/s)	Supply Pressure (Bar)	Conveying Velocity C1 (m/s)
0.05	1.00	5.50	30.00	9.39	52.17	0.0408	201.3	30.45
0.06	1.4	9	40	15.37	71.14	0.04896	241.3	30.49
0.07	1.7	11	40	18.78	74.53	0.05712	271.3	31.63
0.08	2	12.9	40	22.02	76.47	0.06528	301.3	32.55

Table A1.6: Scaled Conveying Characteristics Flurospar Scaling Results at 0.053 m pipeline bore

Polyethylene Pellets: Conveying Characteristics and Scaling Analysis

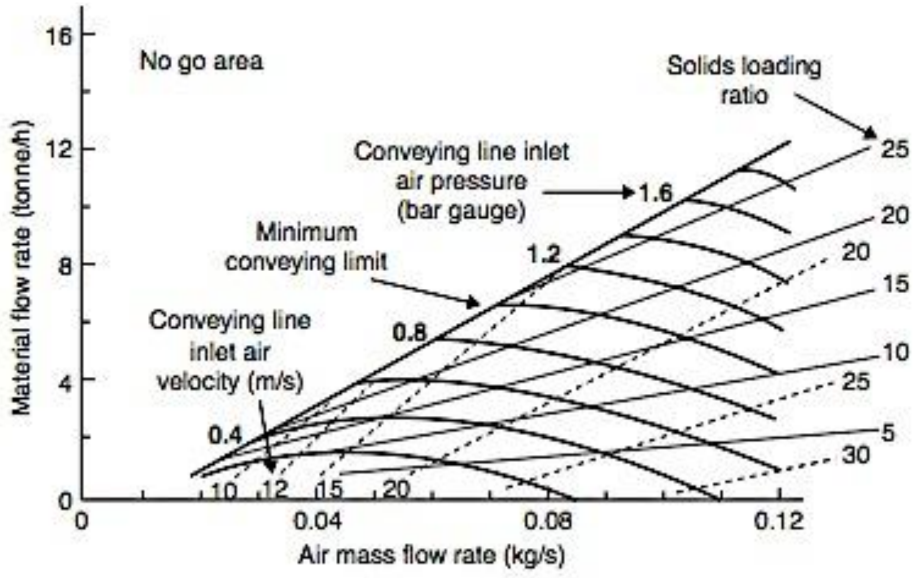

Figure A1.6: Polythene Pellets Conveying Characteristics in a 50 m Pipeline with 53mm Bore, and 9 Bends with D/d ratio of 24

Polyethylene Pellets	Initial Conveying Length (m)	50	Scaled Conveying Length	41				
Air Mass Flow Rate (kg/s)	Conveying Line Pressure Drop (bar)	Initial Material Mass Flow Rate (tonne/h)	Initial Solids Loading Ratio	Scaled Material Mass Flow Rate (tonne/h)	Scaled Solids Loading Ratio	Volumetric Flow Rate of Air (m^3/s)	Supply Pressure (Bar)	Conveying Velocity C1 (m/s)
0.06	0.20	1.00	6.50	1.22	5.65	0.04896	121.3	60.65
0.08	0.6	3	11.5	3.66	12.70	0.06528	161.3	60.81
0.1	0.9	5.5	15	6.71	18.63	0.0816	191.3	64.09
0.12	1.8	11	25	13.41	31.05	0.09792	281.3	52.30

Table A1.7: Scaled Conveying Characteristics Polyethylene Pellets Scaling Results at 0.053 m pipeline bore

Wheat Flour: Conveying Characteristics and Scaling Analysis

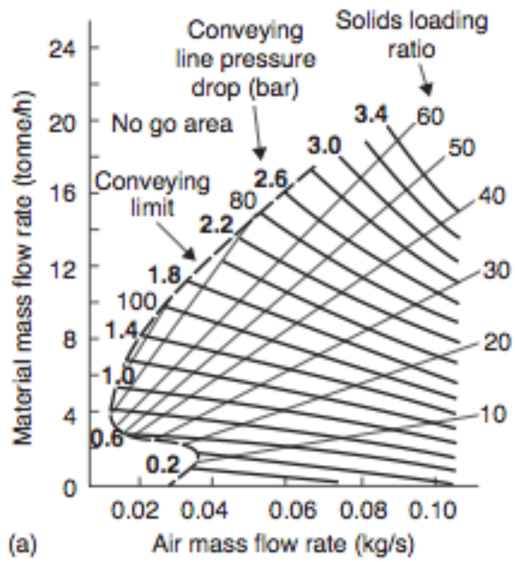

Figure A1.7: Wheat Flour Conveying Characteristics in a 50 m Pipeline with 53mm Bore, and 9 Bends with D/d ratio of 24

Wheat Flour	Initial Conveying Length (m)	50	Scaled Conveying Length	41				
Air Mass Flow Rate (kg/s)	Conveying Line Pressure Drop (bar)	Initial Material Mass Flow Rate (tonne/h)	Initial Solids Loading Ratio	Scaled Material Mass Flow Rate (tonne/h)	Scaled Solids Loading Ratio	Volumetric Flow Rate of Air (m^3/s)	Supply Pressure (Bar)	Conveying Velocity C1 (m/s)
0.04	1.80	10.00	65.00	12.20	84.69	0.03264	281.3	17.43
0.06	2.4	14	70	17.07	79.04	0.04896	341.3	21.55
0.08	3	17	60	20.73	71.99	0.06528	401.3	24.44
0.1	3.4	18	50	21.95	60.98	0.0816	441.3	27.78

Table A1.8: Scaled Conveying Characteristics Wheat Flour Scaling Results at 0.053 m pipeline bore

Coal Pearls: Conveying Characteristics and Scaling Analysis

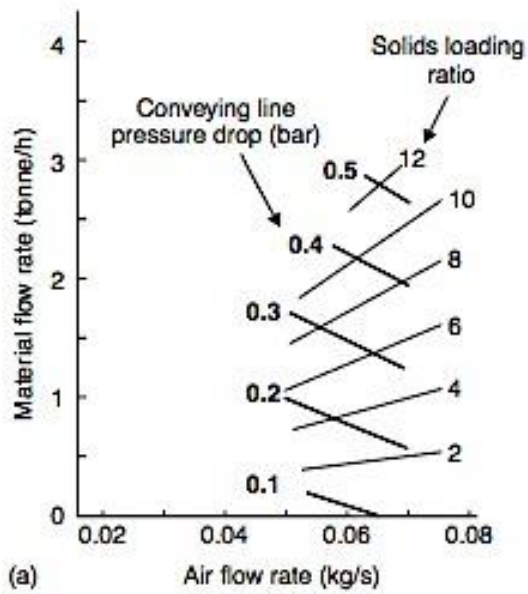

Figure A1.8: Coal Pearl Conveying Characteristics in a 35 m Pipeline with 53mm Bore, and 8 Bends with D/d ratio of 5

Coal Pearls	Initial Conveying Length (m)	50	Scaled Conveying Length	41				
Air Mass Flow Rate (kg/s)	Conveying Line Pressure Drop (bar)	Initial Material Mass Flow Rate (tonne/h)	Initial Solids Loading Ratio	Scaled Material Mass Flow Rate (tonne/h)	Scaled Solids Loading Ratio	Volumetric Flow Rate of Air (m^3/s)	Supply Pressure (kN/m^2)	Conveying Velocity C1 (m/s)
0.05	0.03	1.70	6.50	0.84	3.89	0.04896	121.3	50.54
0.06	0.04	2.1	11.5	2.52	8.75	0.06528	161.3	45.61
0.07	0.05	2.7	15	4.62	12.84	0.0816	191.3	44.86

Table A1.9: Scaled Conveying Characteristics Coal Pearls Scaling Results at 0.053 m pipeline bore

Appendix 2: Material Properties

- All Conveying Data included in Appendix One is sourced from

[13] Mills, David. "Appendix 1: Determination of Relevant Material Properties." *Pneumatic Conveying Design Guide*, 2nd ed., Elsevier Butterworth-Heinemann, 2004, pp. 595–616.

Table A2.1: Particle and Bulk Material Properties of Validation Parameters

	Mean Particle Size (micrometer)	**Bulk Density (kg/m^3)**	**Particle Density (kg/m^3)**	**Compaction (%)**	**Permeability (m^3s/kg *10^-6)**	**Vibrated de-aeration Rate (m/s *10^-3)**
Ordinary Portland Cement	14	1070	3060	40	0.71	3
Iron Powder	64	2380	5710	34	0.34	7
Flurospar	66	1580	3700			
Wheat Flour	90	510	1470	37	1.3	6.2
Magnesium Sulphate	370	1380	2355	29	6.3	17
Granulated Sugar (Fresh)	460	890	1580	10	20	13
Polyethylene Pellets	4000	540	910	5	420	60
Coal Pearls	10000	690	1320			

Ordinary Portland Cement:

Ordinary Portland cement is conveyed widely by industry. It has dense and dilute phase flow capability. It undergoes sliding bed flow in dense phase conveying. The minimum dilute phase conveying velocity for cement is approximately 10 m/s.

Iron Powder:

Iron powder conveys well under standard dilute flow conditions. It has dense phase flow capabilities and good air retention properties.

Fluorspar:

Fluorspar has dense phase flow capability with a minimum conveying velocity of 7 m/s. Its mean particle size places it in the transitional range between dense and dilute phase conveying characteristics.

Wheat Flour:

While wheat flour has a relatively low average particle size due to its air retention properties in is capable of being conveyed at low velocities in dense phase flow. The dense phase wheat flour displayed sliding bed flow characteristics.

Magnesium Sulphate:

Magnesium Sulphate is granular and has no dense phase conveying capability. It's minimum dilute phase conveying velocity is 14 m/s, however it has a comparably low material flow rate at this velocity.

Polyethylene Pellets:

Polyethylene Pellets have a low melting point and is therefore suited to low velocity dense flow conveying. This material exhibits highly consistent particle characteristics. This material has been shown to convey at velocities as low as 3 m/s. This material has a high permeability and conveys in short plugs during dense phase flow.

Coal Pearls:

During conveying it is normal for coal to degrade such that conveying characteristics change. Coal "Pearls" have a mean particle size of 10mm and an average max particle size of 20 mm. Coal Pearls are only suitable for dilute phase flow as they are highly friable. Even though the average particle size of coal pearls was much larger than the majority of the validation materials comparably higher material mass flow rates where achieved then some materials with must smaller average diameters.

Appendix 3: Sample Calculations

1. Darcy's Equation

$$\Delta p = \frac{4fL}{d} * \frac{\rho C^2}{2} \left(\frac{N}{m^2}\right)$$

$$\Delta p = \frac{4(0.0045)(95(m))}{0.1(m)} * \frac{1.225 \left(\frac{kg}{m^3}\right) 11 \left(\frac{m}{s}\right)^2}{2} = 31930 \left(\frac{N}{m^2}\right)$$

2. Ideal Gas Equation

$$\rho = \frac{P}{RT}$$

$$1.17 \left(\frac{kg}{m^3}\right) = \frac{101.3 \left(\frac{kN}{m^2}\right)}{0.2871 \left(\frac{kJ}{kg} * K\right) * 300(k)}$$

3. Velocity in Terms of Air Mass Flow Rate

$$C = \frac{4\dot{m}_a RT}{\pi d^2 p} \left(\frac{m}{s}\right)$$

$$8.72 \left(\frac{m}{s}\right) = \frac{40.02 \left(\frac{kg}{s}\right) * 0.287 \left(\frac{kJ}{Kg} * K\right) * 300K}{\pi (0.053)^2 (281.3) \left(\frac{kN}{m^2}\right)}$$

4. Pressure Drop in Positive Pressure System

$$\Delta p_a = \left(p_2^2 + \frac{64fL\dot{m}_a^2 RT}{\pi^2 d^5}\right) - p_2 \quad \left(\frac{N}{m^2}\right)$$

$$1.2 * 10^5 Bar = (101325) \left(\frac{N}{m^2}\right)^2 + \frac{64(0.0045)(10\ m) * 0.02 \frac{kg}{s^2} * 287 \frac{J}{kg} * K * 300K}{\pi^2 0.1^5 m}) - 101325 \quad \left(\frac{N}{m^2}\right)$$

5. Pressure Drop in Negative Pressure System

$$\Delta p_a = p_1 - \left(p_1^2 + \frac{64fL\dot{m}_a^2 RT}{\pi^2 d^5}\right)^{0.5} \quad \left(\frac{N}{m^2}\right)$$

$$11720\ \mathrm{N/m^2} = 101325\ (\frac{N}{m^2}) - \left(101325\ \left(\frac{N}{m^2}\right)^2 + \frac{64(0.0045)(10\ m) * 0.02\frac{kg}{s^2} * 287\frac{J}{kg} * K * 300K}{\pi^2 0.1^5 m})\right)^{0.5}$$

6. Pressure Drop in Positive Pressure System (Adjusted)

$$\Delta p_a = p_{atm}[(1 + \frac{\psi C_2^2}{RT_2})^{0.5} - 1]$$

$$0.07\ kN/m^2 = 101.3\ (\frac{kN}{m^2})[(1 + \frac{1 * 11^{\wedge}2}{287\ \left(\frac{kJ}{kg} * K\right) * 300\mathrm{K}})^{0.5} - 1]$$

7. Pipeline Friction Loss Coefficient

$$\psi = \left(\frac{4\ f\ L}{d} + \ \Sigma k\right) + \ pipeline\ exit\ loss\ coefficient$$

$$35 = \left(\frac{4\ (0.0045) *\ 100m}{0.053(m)} + \ 0.05\right) + \ 1$$

8. Air Supply Pressure in Positive Pressure System

$$p = \frac{1}{2}\{p_{atm} + \Delta p_a + [(p_{atm} + \Delta p_a)^2 + \frac{\dot{m}_p T_1 \Delta p_a}{2.46 C_1 d^2}]^{\frac{1}{2}}\}$$

$$204\ (\frac{kN}{m^2}) = \frac{1}{2}\{101.3\ (\frac{kN}{m^2}) + (1.8 * 10^{-2})(\frac{kN}{m^2}) + [(101.3\ (\frac{kN}{m^2}) + (1.8 * 10^{-2})(\frac{kN}{m^2})^2 + \frac{10\ \left(\frac{\mathrm{Tonne}}{\mathrm{hr}}\right) * 300\mathrm{K} * (1.8 * 10^{-2})(\frac{kN}{m^2})}{2.46\left(11\frac{m}{s}\right) * 0.1^2}]^{\frac{1}{2}}\}$$

9. Conveying Line Pressure Drop in Positive Pressure System

$$\Delta p_c = p - p_{atm}$$

$$98.7\ (\frac{kN}{m^2}) = 200\ \left(\frac{kN}{m^2}\right) - 101.3(\frac{\mathrm{kN}}{\mathrm{m^2}})$$

10. Equivalent Lengths of Bends

$$L_{eb} = \frac{kd}{4f}\ (m)$$

$$0.011 \text{ m} = \frac{0.04 * (0.035\ m)}{4(0.0300)}$$

11. Reynolds Number

$$R_e = \frac{4\dot{m}_a}{\pi d \mu}$$

$$73534 = \frac{1.18\ \left(\frac{kg}{m^3}\right) * \left(13.2\,\frac{m}{s}\right) * (0.081\ m)}{0.00001725\ (\frac{kg}{m} * s)}$$

12. Equivalent Lengths of Entire System

$$L_e = h + 2v + N(L_{eb})(m)$$
$$6.1 \text{ m} = 2 + 2(2) + 2(0.05)$$

13. Linear Scaling Equation

$$m_{p2} = m_{p1} * [\frac{L_2}{L_1}]^2$$
$$19.51\ \left(\frac{\text{tonne}}{\text{hr}}\right) = 16(\frac{\text{tone}}{\text{hr}}) * [\frac{41\ (\text{m})}{50\ (\text{m})}]^2$$

14. Gas to Cloth Ratio

$$\gamma^* = \frac{\dot{V}}{A_F}$$

$$0.002 = \frac{0.016\ \dot{m}\text{^}3/s}{8\ m\text{^}2}$$

Appendix 4: Glossary

Air Retention:

Air retention is a factor that describes materials ability to retain are in spaces between particles (interstitial space).

Bulk Density:

Bulk density is the density of a bulk solid and is independent of the number of particles in the solid. This density includes air spaces between particles. It is determined by diving the mass of the material by the volume occupied by the material.

Bulk Solid:

A bulk solid is a group of particles large enough for the mean of any material property is not dependent on then number of particles in the group.

Cohesive Strength:

Determined via testing outlined in ASTM D-1628 and ASTM D-6773, this is the bonding strength between particles. Coarse materials such as sand have a low cohesive strength

Compaction:

Material compaction is the amount a material is pressed onto itself reducing air space between particles in bulk solids and increasing particle adhesion.

Friction Factor:

The friction factor is the Darcy Friction Factor used to predict the energy loss in a pipe due to friction based on fluid velocity.

Mean Particle Size:

Mean particle size is the average particle diameter or particles in a bulk solid.

Particle Density:

Particle density is the density of a group of particles unlike bulk density it does not include air spaces between particles.

Permeability:

Material permeability is a factor that describes the ability of air to pass through a bulk solid under a pressure differential.

Solids Loading Ratio:

The solids loading ratio is the ratio between the mass flow rate of material in the system and mass flow rate of air in the system. This value is used to differentiation dense and dilute phase flow.

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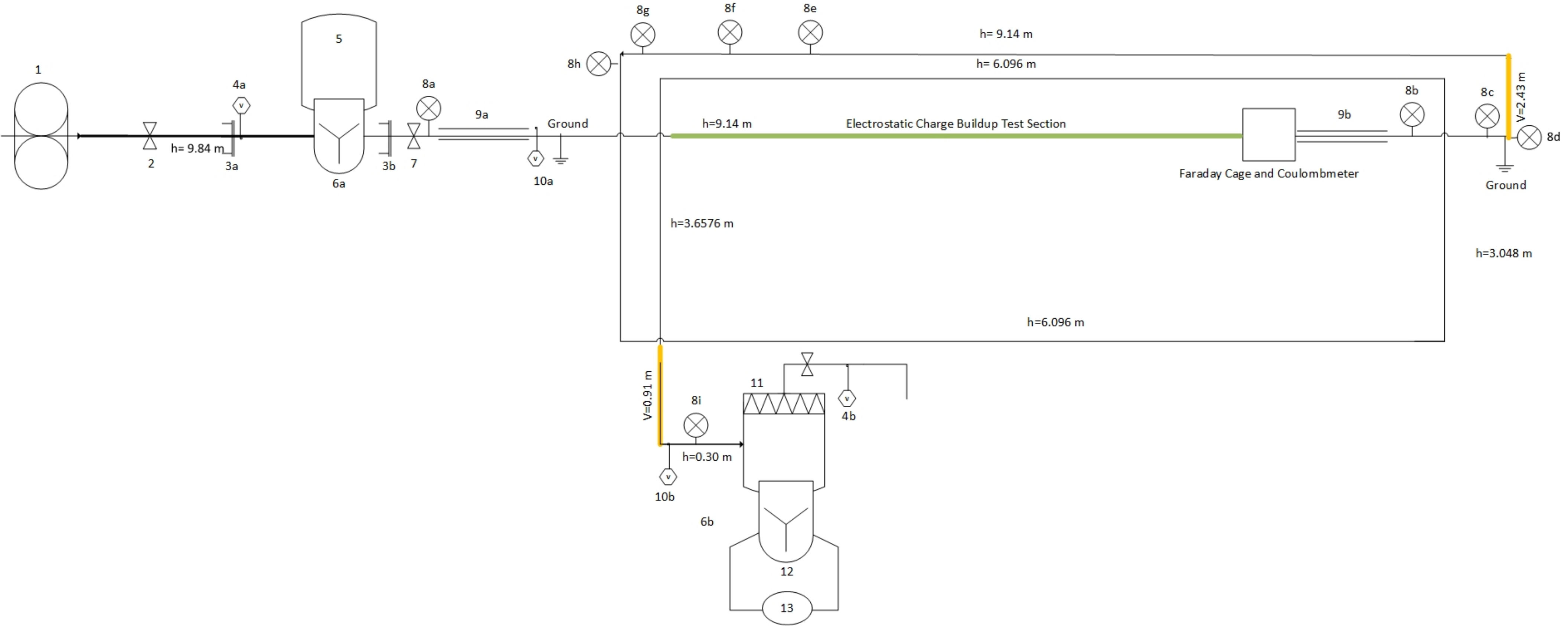

1
2
h= 9.84 m
3a
4a
5
6a
3b
7
8a
9a
Ground
10a
8h
8g
8f
8e
h= 9.14 m
h= 6.096 m
h=9.14 m
Electrostatic Charge Buildup Test Section
Faraday Cage and Coulombmeter
9b
8b
8c
V=2.43 m
8d
Ground
h=3.6576 m
h=3.048 m
h=6.096 m
V=0.91 m
8i
h=0.30 m
10b
11
4b
6b
12
13