PERMEABILITY OF BULK WOOD PELLETS WITH RESPECT TO AIRFLOW

by

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Abstract

Data on the resistance of wood pellets to air flow are required for the design and control of ventilation and drying of bulk pellets in storage. In this study, pressure drops versus air flows were measured for several sizes of wood pellets, with diameter of 6 mm and lengths varying from 4 to 34 mm. Air flow rates ranging from 0.014 to 0.80 m s^{-1} were used in the experiment. The maximum pressure drop measured was 2550 Pa m^{-1}. Three predictive models - Shedd, Hukill-Ives, and Ergun equations that relate pressure drop to air flow in bulk granular materials were used to analyze the data. The Ergun equation was found to provide the best fit to the data.

Aeration of bulk pellets in storage requires a low airflow. The airflow range used for low permeability tests was from 0.0002 to 0.0220 m s^{-1}. The corresponding measured pressure drop ranged from 0.18 to 8.30 Pa m^{-1} for low permeability tests. Three models were investigated and compared for the low permeability data. The increase in moisture content over a wider range of airflows (0.0042 to 0.7148 m s^{-1}) showed a slight decrease in the resistance to airflow due to increased moisture content.

Broken and fines are produced when pellets are handled. The resistance to air flow for wood pellets was measured in the presence of fine materials. Fines were defined as broken pellets passed a 4 mm sieve. The average geometric diameter of the fines was 0.75 mm. The pressure drop for pellets mixed with fines ranged from (2.0 to 191.2 Pa m^{-1}) and (7.9 to 1779.0 Pa m^{-1}) for 1% and 20% fines content (mass basis) respectively. Coefficients of Hukill and Ives' equation for pellets were estimated as a function of percent fines content

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Symbol	Meaning (common units
ΔP	Pressure drop in bed (Pa)
a_i	Equation constant
b_i	Equation constant
V	Air flow rate (m^3 s^{-1} m^2)
L	Bed length (m)
A,B	Equation constant
μ	Permeability of porous media (m^2 s^{-1} Pa^{-1})
μ	Air viscosity (Pa s)
G	Granular permeability
R,S	Equation constant
ε	Porosity of bulk solid
ρ	Density (kg m^{-3})
Φ	Shape factor
d_v	Characteristic dimension (m)
X_i	Equation constant
M	Moisture content (% w.b.)
α,β,γ	Equation constant
Q	Flow rate (m^3 s^{-1} m^2)
a,b,c,d	Equation constant
mc	Moisture content % (w.b.)
fm	Fine material content (%)
f	Fine material content (%)
k_1,k_2	Equation constant
C_i	Equation constant
D	Equivalent diameter of bed particles (m)
SCFM	Standard cubic foot per minute
S_y	Standard deviation of estimates
N	Number of data points
D_p	Effective particle diameter (m)
a_v	Specific surface area of a particle (m^2 m^{-3})
°C	Celsius
ρ_b	Bulk density of seed (kg m^{-3}), crn bulk density (kg m^{-3})
ρ_p	Single pellet density (kg m^{-3})
ρ_k	Corn kernel density (kg m^{-3})

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Dedicated to:

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My Husband, Hooman

and

My Brothers, Fardad, Farzad and Fahim

Co-Authorship Statement

Three chapters of the thesis have been submitted or will be submitted for publication in refereed journals. The co-authors include S. Sokhansanj, A. Lau, C.J. Lim, X. Bi and S. Melin.

My contributions include:

Planning the experiments

Conducting all laboratory work and developing the predictive models;

Performing experimental data analyses;

Being the principal author of the manuscripts.

CHAPTER 1
INTRODUCTION

1-1. Background

Wood Pellets are a form of compacted biomass to increase the density of the fuel and thus making it more economical to transport over longer distances. Most pellets are made from sawdust and ground wood chips, which are waste materials from trees used to make furniture, lumber, and other products. Resins and binders (lignin) occurring naturally in the plant material hold the sawdust together to make a pellet, so a pellet does not contain additives.

Other materials, like straw, corn, nut hulls and similar can also be used to produce pellets, but those are less common. Pellets are cylindrical with a wide ranging diameter from a few mm to almost 25 mm. Pellets of interest in this thesis are 5-6 mm in diameter and 15-25 mm in length.

One of the main advantages of wood pellets compared to other commonly used biomass fuels (wood chips and logs) is their convenience: bags of pellets stack compactly and store easily, their uniform and small shape allows them to flow making the automation of fuel handling easy. The small size of pellets also allows for precisely regulated fuel feed and in turn, combustion air can be regulated easily for optimum burn efficiency. High combustion efficiency is also due to the uniformly low moisture content of pellets (typically 7-8%, compared to 30-35% moisture content in wood chips), and this means a high heat output and a very low level of unwanted emissions.

As a biomass fuel, pellets offer the advantages of sustainable energy supplies through renewable raw materials. In addition, pellets are a by-product, not a primary user, of these renewable materials, and using pellets also helps reduce the costs and problems of waste disposal (Velimir Šegon, www.woodpellets.ca)

Measurement of emissions from wood pellet burners has shown that the amount of particulate matter in the exhaust air is often less than 10 mg m^{-3}, thus meeting most stringent environmental requirements. Pellet heating systems also are CO_2 neutral, because the quantity of CO_2 emitted during combustion is equal to the CO_2 absorbed by the tree during its growth. With the high efficiency burners developed in recent years, other emissions such as NO_x and volatile organic compounds are very low, making this biofuel of the most non-polluting heating options available (SWBC official website).

Using sawdust as fuel in comparison with natural gas can reduce the amount of CO_2 from 421529 g/tonne to 256329 g/tonne. It also reduces the amount of other pollutants like CO, NO_x, N_2O, VOC, PM, SO_x and aldehyde to a great extent (Magelli et al. 2007). A comparison between the total emission factors of wood pellets versus natural gas is reported by Megalli et al. (2007) as shown in Table 1.1.

Table 1.1 Total emission factors in g/tonne wood pellets

Pollutant	Production with sawdust as fuel	Production with natural gas as fuel
CO_2	256329	421529
CO	836	854
CH_4	105	1024
N_2O	13.7	16.6
NO_x	6065	6097
VOC	1510	1725
PM	907	916
SO_X	3780	3862
aldehyde	1.73	1.73
NH_3	6.00	9.81

Because of their economics and environmental benefits, wood pellets are used increasingly as a substitute for fossil fuels. As solid fuels, pellets are handled frequently and kept in confined stores from the time of their production to the time of their use. Spontaneous combustion of long-term storage of wood pellets is a long-standing practical problem. To reduce potentials for spontaneous combustion, it is recommended to prevent the development of temperature and moisture gradients through well managed ventilation.

1-2. Literature review

1-2-1. Air flow pressure drop along packed beds

For the past fifty years researchers have developed semi-empirical and empirical equations to describe pressure drop versus airflow for a specific product. ASAE D272.3 (ASABE 2007) provides airflow versus pressure drop for 40 granular products. These include data for small seeds such as clover to large particles such as alfalfa pellets, potato, and bell peppers, and ear corn. The reported data covers airflows from 0.005 to almost 1.0 m

s^{-1}. (Note: this thesis uses the units for airflow either as m s^{-1} or as m^3 s^{-1} m^{-2}). For some products such as wheat and corn the reported data covers airflow ranges as low as 0.0002 m s^{-1}. The plotted data are all in a log-log scale. ASABE (2007) gives the following semi-empirical equation to represent the airflow versus pressure drop data:

$$\frac{\Delta P}{L} = \frac{aV^2}{\ln(1 + bV)} \qquad (1)$$

which is in the form of Hukill and Ives (1955) equation, ΔP is pressure drop (Pa), L is bed depth (m), V is airflow rate (m s^{-1}) and a, b are constants. ASAE D272.3 lists values for *a* and *b* for a specified range of airflow. The simplest and most widely used equation for expressing the relationship between the pressure drop and airflow is Shedd (1953) equation:

$$V = A\left(\frac{\Delta P}{L}\right)^B \qquad (2)$$

where A and B are constants. Darcy's law defines permeability as a constant to equate velocity with static pressure:

$$V = \mu\left(\frac{\Delta P}{L}\right) \qquad (3)$$

where μ is the permeability of porous media. (m^2 s^{-1} Pa^{-1})

According to Darcy's law the pressure drop varies linearly with the velocity. The permeability coefficient is an indication of media porosity. The permeability coefficient is a function of the pores structure and the fluid viscosity (Greenkorn, 1983). The greater the resistance coefficient is, the greater the pressure drop is created in the porous media. A higher value of permeability means lower pressure drop for the porous media.

Segerlind (1982) defines a granular permeability G where airflow and pressure drop are non linear,

$$G = \frac{V}{(\frac{\Delta P}{L})} = A(\frac{\Delta P}{L})^{B-1} \quad (4)$$

Equation (4) is used to develop flow streams within a bulk material. Hunter (1983) suggested using the following equation to describe the airflow-pressure drop relationship:

$$\Delta P = RV + SV^2 \quad (5)$$

where R and S are product-dependent constants. Compared to Hukill and Ives equation (1), this equation can be easily applied to non-uniform airflow distribution in stored grain. Hunter (1983) fitted equations (2) and (5) to airflow resistance data from the literature and mentioned that R and S values are related to a and b by the following relationships:

$$R = 1.12\left(\frac{a}{b}\right) \quad \text{and} \quad S = 0.346b$$

Hunter (1983) gives values for a and b for 28 products.

Except the above mentioned empirical equations, there are some semi-theoretical and theoretical equations to be used in this area. Garret and Brooker (1965) used the method of Burke and Plummer (1928) for predicting the pressure drop in a bed of agricultural materials which was based on the summation of the drag forces acting on individual particles. Their predicted pressure drop didn't agree with the measured values by Shedd (1953).

Ergun (1952) developed the following fundamental equation to calculate pressure drop in a packed bed:

$$\frac{\Delta P}{L} = 150\,\frac{(1-\varepsilon)^2}{\varepsilon^3 \emptyset^2}\frac{\mu V}{d_v^2} + 1.75\frac{1-\varepsilon}{\emptyset \varepsilon^3 d_v}\rho V^2 \quad (6)$$

where ε is porosity of bulk solids (fraction), V is air velocity (m s^{-1}), μ is air viscosity (Pa.s), ρ is air density (kg m^{-3}), ϕ is a shape factor and d_v (m) is a characteristics dimension of the particle. Woodcock and Mason (1987) describe the development of equation (6) from fundamental fluid mechanics. On the right hand side of equation (6), the first term is a linear function of velocity. This term represents the viscous effect. The second term is a second order function of airflow. This term represents the kinetic effect.

Equation (6) is useful for a packed bed of particles that have a well defined shape factor and characteristic dimension. These parameters are not well defined for most irregular shaped or non spherical particles.

Ray et al. (2004) measured the airflow resistance of four types of commercially available pelleted feed varying in shape and dimensions. They used Equation (2) to express the relationship between the pressure drop and airflow rate. Sokhansanj et al. (1993) investigated the airflow resistance for alfalfa cubes, clean pellets, and fines mixed with pellets. Equation (2) fitted their data better than Equation (1). The constant A showed a strong dependence on the percentage of fines in the mix whereas B was not sensitive to fines and was assumed constant.

Several factors affect the resistance of bulk granulated biomass to airflow including the air viscosity and density, porosity of the bulk material, orientation of the particles in bulk, size, and shape and particle surface condition.

Montross et al. (2005), Chung et al. (2001), Giner et al. (1996), Sacilik et al. (2004), Kristensen et al. (2000) and Pagano et al. (2000) have reported data on resistance to airflow for corn, soybean, soft red and white wheat, baled hay, grain sorghum and rough rice, wood chips and oat seeds as affected by air velocity, bulk density, moisture, fine materials, type of wood. Ray et al. (2004) tested the effect of bin shape (circular, square or rectangular) on the pressure drop in the beds of above mentioned materials and the results have indicated that the test apparatus cross section had no effect on the measured airflow resistance.

1-2-2. Effect of particle size and bulk density on pressure drop air flow data

Calderwood (1973) considered the effect of increased bulk density (packing) and moisture content on the pressure drop. He found that the data from his tests were related to the data of Shedd (1953) by a Shedd's curve multiplier (SCM). The SCM was the ratio of the pressure drop through a grain mass to the pressure drop predicted by Shedd's curve for the grain at the same airflow rate. With a fill density of 639 and 729 kg/m^3, the SCM was 1.18 and 2.72, respectively, for rough rice at a moisture content of 15.2%.

Bern and Charity (1975) studied the effect of the grain bulk density on the airflow resistance of corn. An increase in the bulk density resulted in an increase in the airflow resistance per unit depth of corn. They suggested the following empirical equations:

$$\Delta P = X_1 + X_2 \frac{(\frac{\rho_b}{\rho_k})^2 V}{(1 - \frac{\rho_b}{\rho_k})} + X_3 \frac{\left(\frac{\rho_b}{\rho_k}\right) V^2}{(1 - \frac{\rho_b}{\rho_k})^3} \quad (7)$$

Where ρ_b is the corn bulk density (kg/m^3), ρ_k is the corn kernel density (kg/m^3), X_1, X_2 and X_3 are constants.

Molenda et al. (2005) also investigated the effect of bulk density in resistance to airflow for seeds. Montross et al. (2005) indicated the permeability of corn, soybeans, and soft red and white winter red as affected by bulk density. The resistance of corn, soybeans, soft white wheat, and soft red wheat were measured as a function of filling method, bulk density, and moisture content. Low bulk density corn and soybeans had the lowest resistance coefficient, between 863 and 604 Pa s/m^2 (or permeability between 2.12×10^{-8} and 3.03×10^{-8} m^2, respectively). Increasing the bulk density by 7% decreased the permeability by approximately 40%. Wheat had the highest resistance, between 3112 and 1591 Pa s/m^2 (or a permeability between 5.88×10^{-9} and 1.15×10^{-8} m^2, respectively) at the low bulk density. A 4.7% increase in bulk density resulted in a 41% greater resistance coefficient for white and red wheat. The effect of kernel orientation was not as significant as changes in the porosity. Darcy's law was valid for predicting natural convection currents during non-aerated storage.

1-2-3. Effect of moisture content on pressure drop

One of the major factors affecting the resistance to airflow is the moisture content of materials tested. Giner et al. (1996) did tests on the wheat with different moisture content. First they tested the three existing models (Shedd, Hukill and Ives and Ergun) and found Ergun type equation fitted the data best. To develop the equation which can express the effect of moisture content, they modified the Ergun type equation as follows:

$$\frac{\Delta P}{L} = (\alpha - \gamma M)V + \beta V^2 \qquad (8)$$

where ΔP is the pressure drop per meter depth of material in Pa m^{-1}, L is the bed length in m, M is the moisture content % (w.b), and V is the air velocity in m s^{-1}. Equation (8) indicates that only the linear term of the Ergun-type equation is the function of moisture content. The second term that represents turbulent flow does not depend on moisture content. Equation 8 states that the higher the moisture content is the lower the pressure drop would be.

Chung et al. (2001) did the moisture content tests in beds of grain sorghum and rough rice and figured out the same trend in data. He proposed an equation including the effects of both moisture content and fine materials.

$$\Delta P = a(Q) + b(Q)^2 + c(Q)(mc) + d(Q)(fm) \quad (9)$$

where ΔP is the static pressure drop per meter depth of grain (Pa/m), Q is the airflow rate in $m^3\ m^{-2}s^{-1}$, mc is the grain moisture content (% w.b), fm is the fine material content (%) and a, b, c and d are regression factors. Static pressure drops for both grain sorghum and rough rice tended to increase with decreasing grain moisture content. They also found that among three variables (airflow rate, moisture content and fine materials), airflow had the most significant effect on the resistance to airflow.

Other researchers including Li et al. (1994), Siebenmorgen et al. (1987), Sokhansanj et al. (1993), Pagano et al. (2000) and Montross et al. (2005) have also verified a decrease in pressure drop with an increase in moisture content.

1-2-4. Effect of fine material contents on pressure drop

The other major factor affecting the airflow resistance is the percentage of fine materials in the bed. Sokhansanj et al. (1993) has done tests in beds of alfalfa pellets containing fine materials in it. To be consistent with the published ASAE D272 (ASABE 2007), Sokhansanj et al. (1993) provided a correction to equation 2 for the fines content,

$$\left(\frac{\Delta P}{L}\right)_{fines} = \left(\frac{\Delta P}{L}\right)_{clean} [1 + (0.361 + 1.298V)fm] \quad (10)$$

where $(\Delta P/L)_{clean}$ is calculated from equation 2 for clean pellets; fm is the mass fraction of fines and broken in the mix; $(\Delta P/L)_{fines}$ is the pressure drop of pellets mixed with fines.

Sokhansanj et al. (1993) estimated $a=1.8\times10^4$ and $b=68.72$ for clean uniform size alfalfa pellets (6.2 mm diameter). Increasing the fine material content in the bed increased the resistance of bulk material to airflow.

Chung et al. (2001) developed equation 9 for beds of sorghum and rough rice which includes both the effects of moisture content and fine material. In grain sorghum, static pressure drop tended to increase with increasing amounts of fine material. In rough rice, the static pressure drop decreased as fine material concentration increased, possibly because of larger particle size of fine material compared to grain sorghum.

The effect of fine material was also investigated by Giner et al. (1996) in beds of wheat. They showed the following relation between pressure drop and airflow with two constants k_1 and k_2.

$$\frac{(\frac{\Delta P}{L})_{corrected}}{(\frac{\Delta P}{L})_{clean}} = k_1 + k_2 f \tag{11}$$

where f is the fine fraction in the bed. Sacilik (2004) also investigated equations for the effect of fine materials in beds of granular materials (poppy seeds). They also included the effects of moisture content in combination with fines to develop the following empirical equation:

$$\Delta P = C_1 Q^2 + C_2 M Q + C_3 \rho_b Q + C_4 f\, Q \tag{12}$$

where ΔP is the pressure drop per unit depth in Pa/m; Q is the airflow rate in m s^{-1}; M is the moisture content in % d.b.; ρ_b is the bulk density of the seed in kgm^{-3}; F is the fines content in %; and C1, C2, C3 and C4 are regression coefficients.

1-3. Ventilation systems design

As mentioned earlier to prevent spontaneous combustion in storages, aeration and ventilation schemes are devised to keep the moisture content and temperature of pellets down and uniform throughout storage structure. Pressure drop data vs. airflow rate are required in order to design ventilation systems including size and power requirement for the fans and blowers.

Fans or blowers are devices by which air is moved. The operation of a fan is characterized by the volume of air it moves and the total pressure associated with the volume of air (McLean, 1989). The output of the blower should be able to overcome the system pressure in order to deliver certain amount of air. Figure 1.1 shows a blower's airflow-pressure curve and the system's airflow pressure drop. The intersection of the two curves point A is the calculated operating conditions when the blower is operated in conjunction of the system to be ventilated.

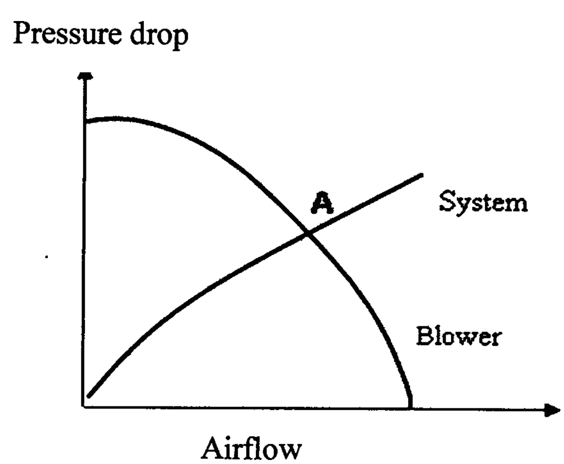

Figure 1.1 Blower performance curve and system curve. Interaction A is the operating condition.

1-4. Objectives

The existing pressure drop data for feed pellets does not cover low airflow ranges prevalent in storing and aeration of wood pellets. Furthermore size distribution of wood pellets and the characteristics of fines are different than those for pellets feeds.

The purpose of this study was (1) to determine the effects of airflow rates and particle size on pressure drop (2) to determine the permeability to low air flow of bulk wood pellets and to develop equations that relate differential static pressures in beds of bulk wood pellets subject to forced airflow (3) to investigate the effect of moisture content on the static pressure drop and (4) to develop experimental data on permeability of bulk wood pellets to air flow in the presence of fines fractions, and (5) to develop an equation to predict pressure drop as a function of airflow rate and fines content.

Objective 1 is addressed in chapter 2 while objectives (2,3) and (4,5) are addressed in chapters 3 and 4 respectively. And finally the conclusions for the research and some recommendations for the future work are discussed in chapter 5.

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CHAPTER 2[1]

AIR FLOW VERSUS PRESSURE DROP FOR BULK WOOD PELLETS

2-1. Introduction

Wood pellets are compacted ground wood materials, whereby natural resins and lignin in wood bind the loose particles together. The most common dimensions of wood pellets produced in Canada are 6 mm in diameter and up to 30 mm in length. The moisture content of pellets is in the range of 5-7% wet basis. While individual pellets have a particle density of about 1.2 g cm^{-3}, the bulk density of pellets ranges from 600 to 750 kg m^{-3}.

Solid biofuels such as wood chips, bark, and grasses have low volumetric energy content due to their low bulk density. In regions especially those away from the Equator, the harvest season for biomass is short. Storage spaces are necessary to safely keep a large supply of feedstock for timely delivery to a biorefinery throughout the year. The biomass storage period may last for one day to several months. It is important to maintain the stored pellets under cool and dry conditions, and uniform temperature to prevent moisture migration and self heating.

In wood pellets storage, slow oxidation seems to be the first step in a self-heating process, as the fuel is too dry to sustain any significant biological activity (Wadso, 2007). It was postulated that an initial temperature rise in storage is due to microbial activity, followed by exothermic oxidation when the temperature is greater than 60°C and finally thermal cracking takes place at temperatures higher than 200°C (Liodakis et al., 2002). Hydrolysis, pyrolysis and oxidation

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reactions (Kubler et al., 1987) are among major factors contributing to heat production. Preventive methods are necessary to avoid storage fire, which is dangerous and cannot be easily controlled. Forced ventilation is a management tool to prevent excessive concentration of toxic gases such as CO, CO_2 and CH_4 and to prevent the possibility of spontaneous combustion.

The design of a ventilating system requires pressure drop versus air velocity data for a bed of packed materials and its associated air delivery and exhaust system. These data guide the selection of an optimum size blower that would provide the necessary ventilation air flow rate (Giner, 1996). An overall pressure drop-air flow relationship is also useful for studying air flow patterns within the bulk of solid particles. These air flow streamlines can identify critical spots that remain unventilated and hence experience a moisture content and temperature increase that may lead to self-heating and spontaneous combustion. These streamlines also assist in designing and locating the ventilation ports to minimize hot spots. The objective of this research is to develop equations that relate differential static pressures in a column of bulk wood pellets subject to forced ventilation.

Factors that affect the resistance of bulk pellets to airflow include air viscosity and density; porosity of the bulk material; size, shape and surface condition of particles; and orientation of the particles in bulk, These factors are highly interdependent; it is difficult to develop a unique model to relate the pressure drop to airflow as a function of these factors (Li and Sokhansanj, 1994).

Sokhansanj et al. (1993) fitted Shedd's equation (Shedd, 1953) to experimental data for alfalfa pellets and cubes,

$$V = a_1(\Delta P)^{b1} \qquad (1)$$

where V is frontal air flow rate in $m^3\ m^{-2}\ s^{-1}$ and ΔP is pressure drop in Pa m^{-1}. The constants a_1 and b_1 were estimated for one size of cubes and three sizes of pellets. They also estimated a_1 and b_1 for 5 to 25% fine contents in the 6.4 mm diameter pellet samples.

The ASAE D272.3 standard (2007) provides data on air flow versus pressure drop for some forty materials, mostly agricultural crops. The data are presented graphically in a logarithmic scale. Hukill and Ives (Hukill and Ives, 1955) suggested the following equation that relates air flow to pressure drop for agricultural materials:

$$\frac{\Delta P}{L} = \frac{a_2 V^2}{\ln(1 + b_2 V)} \qquad (2)$$

where ΔP is the pressure drop (Pa), L is the depth of the bed (m), V is superficial or frontal air velocity (m s^{-1}). Constants a_2 and b_2 are tabulated in ASAE D272.3 (2007). The specified airflow range for alfalfa pellets is 0.0053 to 0.63 m s^{-1}.

Ray et al. (2004) investigated air flow versus pressure drop characteristics for feed pellets 4.0 mm, 6.7 mm, and 9.4 mm in diameter as well as cubes having a cross section area of 33.2 mm×34.9 mm. The air flow in their study ranged from 0.0093 to 0.236 m s^{-1}. They investigated three storage container shapes - round, square and rectangular, and two filling methods - loose and tapped. Pressure drop versus air flow was found to be insensitive to the geometry of the container cross section. Tapping increased pressure drop by a maximum of 14% for the small (4 mm) pellets. Ray et al. (2004) presented Shedd's constants A_1 and B_1 for the tested pellets and cubes.

Kristensen and Kofman (2000) published pressure drop versus air flow data for cut willow chips, which were made from newly harvested material and the moisture content was about

55%. They classified the chips according to different size groups. Of particular interest to us are their data on chips with a nominal cutting length of 28 mm; 54% of the chips in this class had actual lengths of 7 -16 mm, and the majority of mass fractions were in the smaller size group (< 16 mm). Variations in particle size were determined to be the largest factor influencing air flow data. Table 2.4 lists the transformed values for *a* and *b* as derived from their study.

Kristensen et al. (2003) published further more data on air flow and pressure drop for wood chips that included large chunks and for 8-mm size wood pellets. Air flow ranged from 0.02 to 0.3 m s^{-1}. Nevertheless, Kristensen et al. (2003) did not have data on ranges in pellet lengths, bulk density, or moisture content of the pellets.

Hunter (1983) made a comparison between the Hukill-Ives model (Eq. 2) and Ergun's model (Ergun, 1952) and suggested the following modified form of Ergun's equation,

$$\Delta P = RQ + SQ^2 \qquad (3)$$

where R=1.12 a_2/b_2 and S=0.346 b_2. The symbols a_2 and b_2 are the constants in Eq. (2). Hunter (1983) reported values for R and S for 28 different grains.

Gayathri and Jayas (2007) reviewed literature on the mathematical modeling of airflow distribution in bulk grain storage. They initiated their review from constituent Eqs. (1) and (2), followed by more complex equations. The Ergun equation is based on dividing the flow regime in a porous packed bed to laminar (viscous) flow and turbulent (dynamic) flow similar to Eq. (3):

$$\frac{\Delta P}{L} = a_3 V + b_3 V^2 \qquad (4)$$

where a_3 and b_3 are constants associated with viscous flow and turbulent flow,

$$a_3 = 150\frac{(1-\varepsilon)^2}{\varepsilon^3 \emptyset^2}\frac{\mu}{d^2} \quad (5)$$

$$b_3 = 1.75\frac{(1-\varepsilon)}{\emptyset \varepsilon^3 d}\rho \quad (6)$$

where bed parameters are porosity ε (fraction), bulk density ρ (kg m^{-3}); equivalent diameter of bed particles d (m); acceleration due to gravity, viscosity of the air fluid μ (Pa s) and the shape factor ϕ.

Gu et al. (2000) instrumented an experimental grain bin with hot wire anemometers to measure the air flow pattern in the grain bin as a function of air entry geometries. They modeled the air stream lines using second order differential equations describing the pressure gradients within the pile (Sokhansanj et al., 1997), and used a technique developed by Brooker (1959) to linearize constants a_2 and b_2 in Eq. (2). The predicted flow patterns agreed reasonably well with the experimental data.

From the reviewed literature it has become clear that the existing data for air flow versus pressure drop for pellets has several shortcomings. Firstly, the data for alfalfa pellets are not consistent. Secondly, the data do not cover low air flow ranges prevalent in storing and aeration of wood pellets. Lastly, the variability in particle lengths and bulk density of pellets and their effects on air flow pressure drop was not investigated. These shortcomings cast uncertainty on the adaption of existing data for feed pellets towards wood pellets. So the objectives were to find the relationship between the pressure drop and air flow as it is affected by particle size (bulk density) and to evaluate the common existing equations for air flow resistance to determine the equation which can express the data best.

2-2. Materials and methods

2-2-1. Experimental apparatus

Figure 2.1 shows a schematic diagram of the laboratory test apparatus. The apparatus consists of a transparent acrylic cylindrical column and instruments for measuring the flow rates and static pressure. The column was 290 mm in diameter and 570 mm in height. Air was introduced at the bottom of the cylinder. A plenum that contained plastic rings was provided for uniform air entry into the cylinder. The source of air was filtered compressed air from a centralized generating station. The average air temperature and relative humidity were 20°C and 30%, respectively. Two float-type in-line flow meters that covered a wide range of flow rates were used. The tested air flows range from a low velocity to near fluidization velocity. The low range flow meter (Model FL-7313 Omega Engineering Inc.) measured the air flow rates between 9.43×10^{-4} to 6.60×10^{-3} $m^3 s^{-1}$. The high range flow meter (Model FL-2093, Omega Engineering Inc.) measured air flow rates up to 4.71×10^{-2} $m^3 s^{-1}$. The measured flow rates were in English units of standard cubic feet per minute (SCFM) with a precision of ±2% full scale.

Pressure drop was measured along the depth of the wood pellets column via an inclined manometer (Model 26 Mark II, Dwyer Instrument Inc.) for preliminary tests and a digital manometer (Model HHP-103, Omega Engineering Inc.) for subsequent tests. The manufacturer's specified pressure range for Model HHP-103 was 0 to 2953 Pa. Four pressure taps were located at four levels 100 mm apart along the height of the column. The lowest tap was 50 mm from the bottom of the sample. Air flow from the compressed air line passed through a series of filters, pressure regulators and through the float-type airflow meter before entering the pellet column.

All tests in this study were conducted in three replicates. For low airflow range (0.0142 to 0.1072 m s^{-1}), pressure drop was measured at 14 levels of airflow rates and for high airflow range (0.1072 m s^{-1} to 0.7148 m s^{-1}) it was measured at 18 levels of flow rates. The ambient temperature and pressure were recorded during each test.

2-2-2. Sample preparation and measurements of physical properties

The wood pellet material ranges from clean uniform sizes to a mixture of different sizes. Table 2.1 lists the characteristics of two types of white wood pellets used in these experiments. Using a sieve shaker (Model TM-5, Gilson Company, Inc.) and trays with openings of 4 mm and 6.7 mm, wood pellets were fractioned to three different size categories- $L>6.7$mm, 4 mm$<L<6.7$mm, and $L< 4$ mm. The orientation of the pellets on the trays during the screening process is very important; they may orient horizontally which is desirable. Some pellets broke into smaller pieces due to the shaker vibration upon classifying the pellets and preparing samples. The length of sieving time was shortened to minimize the pellet breakage. Pellets with $L < 4$ mm considered as fines, and they were discarded.

The length and diameter of about 200 pellets from each of the two remaining fractions were measured using a calliper. Each pellet was also weighed using a digital scale to 0.01 g precision. The ratio of mass over volume was the pellet density. The bulk porosity was determined using the following equation (Mohsenin, 1986):

$$\varepsilon = 1 - \frac{\rho_b}{\rho_p} \qquad (7)$$

where ρ_b is the bulk density and ρ_p is the single pellet or particle density.

The bulk density of wood pellets was determined according to a modified ASAE Standard S269.4 DEC 01 (2007). A cylindrical container 152.4 mm in diameter and 122 mm in height was used for the determination of bulk density. The pellets were poured slowly into the bucket from a height of 500 mm from the bottom of the container until the container was overflowing. Excess material was removed by striking a straight edge across the top. The weight of the material with the bucket was recorded to 0.01g precision. For tapped density, the loosely filled container was tapped on the laboratory bench five times. Filling and tapping was repeated until the container was overflowing. The filled container was weighed to 0.01 g precision. After the net weight of the samples was obtained by subtracting the weight of the empty bucket, bulk density was calculated as the ratio of mass over volume of the bulk materials.

The durability of pellets was measured using a DURAL Tester (Sokhasnsanj and Crerar, 1999). The tester uses 100 g sample subjected to a rotating knife in a sealed container for 30 seconds. The treated sample was sieved through a 4 mm wire mesh sieve. Overs and unders were weighed and their percent mass of the original sample mass was expressed as breakage.

2-3. Results and discussion

Table 2.1 lists the average and range of physical properties of two samples from two different biomass suppliers. The mean diameter of pellets from the two suppliers are virtually the same, at 6.4-6.5 mm, and the mean length of pellets from supplier 1 at 11.0 mm was slightly larger than that from supplier 2 at 10.5 mm. Samples from supplier 2 had a durability of 67.2% compared to those from supplier 1 at 58.1%. Both samples were clean with no dust, though sample 1 had somewhat higher bulk density than sample 2. Samples 1 and 2 had very similar particle density, at 1.13-1.14 g cm^{-3}.

Figure 2.2 shows the length distribution of two samples from one manufacturer. Pellets left on the 6.7 mm screen had a size ranging from 12 to 28 mm, whereas pellets that passed the 6.7 mm screen and remained on the 4 mm screen had a size ranging from 5 to 12 mm.

Eqs. (1), (2) and (4) were fitted to the experimental data for each size category using a non-linear least squares regression method with two software packages - DataFit 8.2 (Oakdale Engineering) and POLYMATH 6.0 (2004). Table 2.3 contains the values of the fitted parameters, their standard errors, and standard deviation of estimates (S_y). S_y expresses the average deviation between experimental and predicted values and is defined as follows:

$$S_y = \left(\frac{\sum_{i=1}^{N}(\text{predicted}_i - \text{experimental}_i)^2}{(N-2)}\right)^{\left(\frac{1}{2}\right)} \quad (8)$$

where N is the number of data points and (N-2) is the number of degrees of freedom.

For the entire range of flow rates (0.0142 to 0.7148 m s^{-1}), the average S_y for samples 1 and 2 in Eq. (1) were 21.69 and 22.15 Pa m^{-1} respectively, while the corresponding values for Eq. (2) were 20.49 and 21.62 Pa m^{-1}. Eq. (3) fitted the data better than the other two equations with an average S_y of 18.90 and 19.65 Pa m^{-1}.

Table 2.4 lists the fitted parameters to Shedd's equation for different materials including alfalfa pellets, feed pellets, 28 mm cut willow chips and 8 mm wood pellets. Shedd's constants for 6.4 mm alfalfa pellets estimated by Sokhansanj et al. (1993) and those estimated by Ray et al. (2004) for 6.7 mm feed pellets were compared. The calculated pressure drops from Ray et al.'s data (2004) were significantly higher those calculated from Sokhansanj et al.'s data (1993). The differences between their calculated pressure drops reached 80% at the low air flow of 0.01 m^3 s^{-1}, though the differences decreased to 38% at greater air flow of 0.28 m^3 s^{-1}. Ray et al.

(2004) recorded a bulk density of 710 kg m^{-3} for 6.4 mm pellets whereas Sokhansanj et al. (1993) recorded a bulk density of 588 kg m^{-3} for similar size pellets. The analyzed data from this study was also shown in Table 2.4. The fitted parameters are much closer to the results derived from 28 mm cut willow chips (Kristensen and Kofman, 2000, Kristensen et al. 2003) than those of 6.4 mm alfalfa pellets and 6.7mm feed pellets (Sokhansanj et al. 1993, Ray et al. 2004).

To observe how our selected equations predict the entire range of air flow rates, percentage error of predicted versus experimental pressure drops was calculated as a function of air flow rate, for mixed sizes of pellets. Figures 2.3 shows that Eqs. (2) and (3) had a lower error at low air flows and had a better fit to the entire range of data. Ergun equation covers laminar flow and turbulent flow regimes and it seems to explain the data best.

Figure 2.4 shows a log-log plot of pressure drop versus air flow rates, ranging from 0.0142 to 0.7148 m s^{-1}, for white wood pellets. As expected, the length of wood pellets affects the bulk density; longer pellets (larger particle size) had a lower bulk density and pressure drop and conversely, shorter pellets had a larger bulk density and larger pressure drop. The highest pressure drop for longer pellets (L>6.7mm) and shorter pellets (4 mm<L<6.7 mm) was 955 Pa m^{-1} and 2488 Pa m^{-1}, respectively. The pressure drop for mixed sizes of pellets fell in between these two extremes. It can also be seen that the plotted data are not linear; an increase of about 32% in bulk density led to almost 1.5 times increase in pressure drop.

2-4. Conclusions

Bulk wood pellets manufactured from sawdust in British Columbia were subjected to air flow in laboratory tests. The pellets had an average diameter of 6 mm and length ranging from 6 to 34 mm. The pellets were screened to three sizes - those with length shorter than 4 mm, between 4 and 6.7 mm, and longer than 6.7 mm. The pressure drop for each of the sample group and their mix was measured over a wide range of air flow rates. The pressure drop was observed to increase with air flow rate and such increases became more profound for higher air flows. Smaller wood pellets had the highest resistance to air flow. Increasing the size of wood pellets or using a mixture of different sizes decreased the resistance. It may be assumed that larger particles will lead to more direct and straight pathways for the air to pass, thus resulting in lower resistance to air flow.

Among the three predictive equations (Shedd, Hukill-Ives and Ergun) studied, the Ergun equation appeared to provide the best fit to the data for the entire range of air flows. This could be attributed to two additive terms representing linear and quadratic function of air velocity for both laminar and turbulent flows in the Ergun Equation.

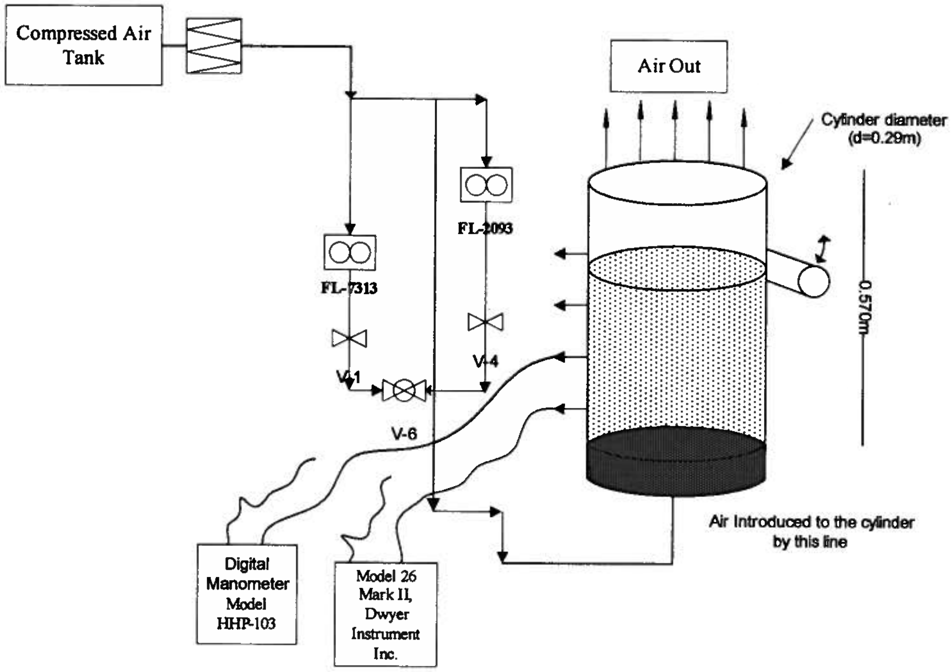

Figure 2.1 Equipment for measuring the resistance of wood pellets to air flows

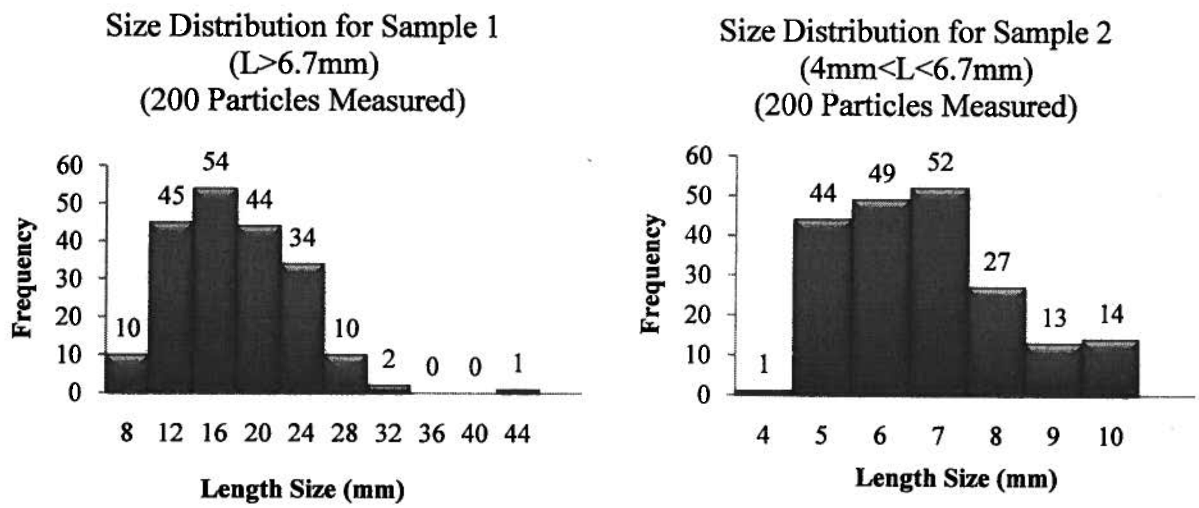

Figure 2.2 Size distribution for sample 1 (L>6.7mm) and sample 2 (4mm<L<6.7mm).

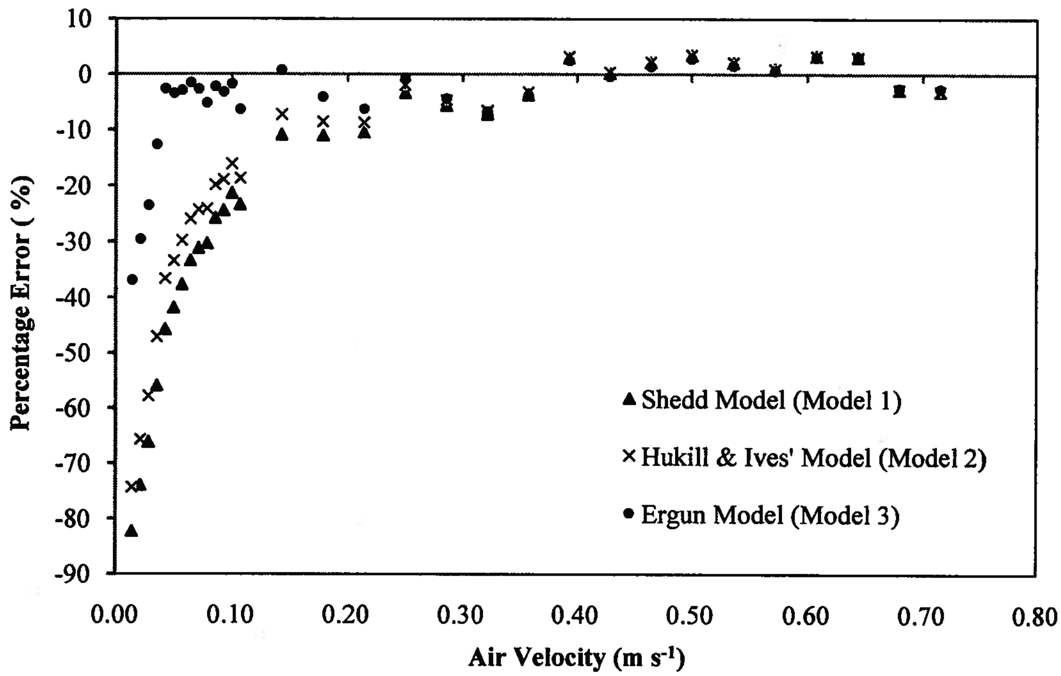

Figure 2.3 **Percentage error in the prediction of pressure drop for mixed sizes of wood pellets as a function of air velocity using three models.**

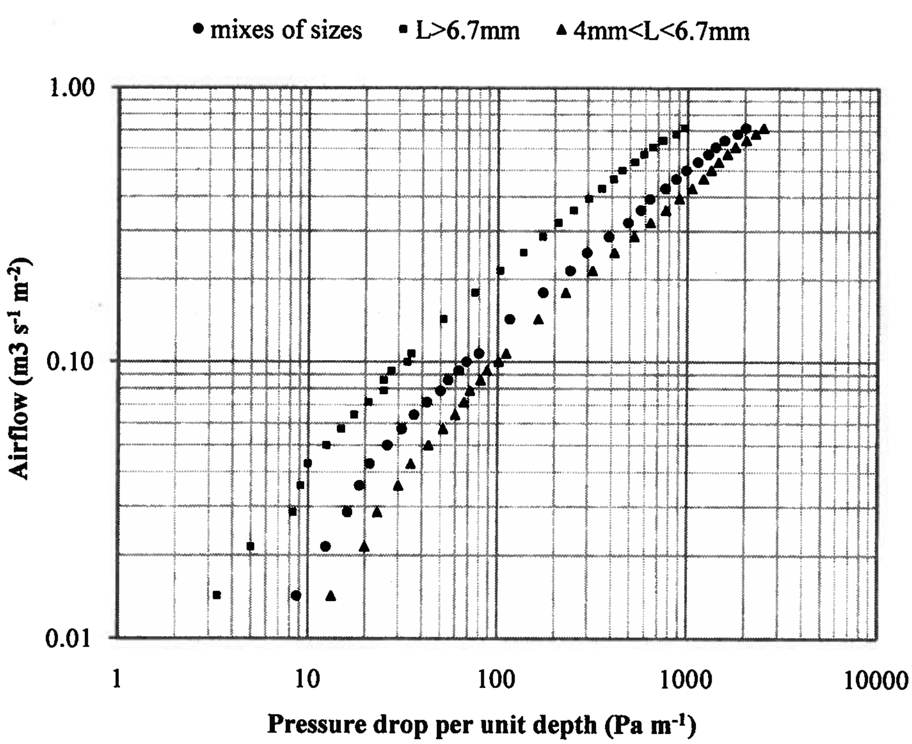

Figure 2.4 **Resistance of white wood pellets with different sizes to air flow**

Table 2.1 Physical properties of pellets made from spruce saw dust

Physical property	Sample 1	Sample 2
Diameter (mm)	6.5[a] (6.3-6.7)[b]	6.4 (6.3-6.5)
Length (mm)	11.0 (3.6-41.2)	10.5 (4.5-36.4)
Moisture content (%)	4.6 (4.5-4.8)	4.6 (4.4-4.8)
Durability (%)	58.1 (56.7-59.5)	67.2 (66.0-68.6)
Bulk density (kg m^{-3})	800 (793-804)	761 (757-774)
Particle density (g cm^{-3})	1.13 (1.03-1.23)	1.14 (1.03-1.26)
Porosity	0.29	0.33

[a] mean value; [b] range of values

Table 2.2 Air flow rate and pressure drop data for three size categories of pellets

Flow rate (m^3 s^{-1})	Pressure drop (Pa m^{-1})		
	Mixed Sizes	L>6.7mm	4mm<L<6.7mm
0.00094	8.7	3.3	13.2
0.00141	12.4	4.9	19.9
0.00943	115.8	51.4	164.4
0.01651	296.4	137.0	413.5
0.01887	387.3	172.7	526.5
0.03067	868.0	408.5	1209.1
0.04247	1556.7	743.2	2021.3
0.04719	2006.3	963.3	2488.1

Table 2.3 Estimated constants for the various predictive models

Equation 1 (Shedd's Equation)

Particle Size	Sample	a_1	b_1	Standard Error		S_y
				a_1	b_1	
Mixed sizes	1	0.0112	0.5482	6.6574E-4	8.1852E-3	25.49
L>6.7 mm	1	0.0198	0.5244	1.0000E-3	8.3829E-3	12.94
4mm<L<6.7mm	1	0.0060	0.5953	3.7568E-4	7.3010E-3	26.66
Mixed sizes	2	0.0127	0.5462	1.0168E-3	1.1319E-2	28.74
L>6.7 mm	2	0.0173	0.5393	1.1082E-3	9.7420E-3	15.57

Equation 2 (Hukill- Ives Equation)

Particle Size	Sample	a_2	b_2	Standard Error		S_y
				a_2	b_2	
Mixed sizes	1	22003.69	452.52	2931.88	337.46	24.35
L>6.7 mm	1	18879.30	43872.48	5469.37	1291.51	12.79
4mm<L<6mm	1	16332.10	41.64	1019.01	8.67	24.34
Mixed sizes	2	18334.52	523.02	3557.07	582.38	28.01
L>6.7 mm	2	13182.17	1300.51	2640.96	1730.79	15.23

Equation 3 (Ergun's Equation)

Particle Size	Sample	a_3	b_3	Standard Error		S_y
				a_3	b_3	
Mixed sizes	1	337.11	3354.26	40.69	72.18	20.84
L>6.7 mm	1	98.77	1687.07	22.06	39.14	11.30
4mm<L<6mm	1	742.88	3764.85	47.96	85.07	24.57
Mixed sizes	2	269.69	2731.73	49.98	88.66	25.60
L>6.7 mm	2	146.09	1731.74	26.82	47.57	13.74

Table 2.4 Constants a_1 and b_1 in Shedd's equation among various materials

Product	a_1	b_1	Air flow range $m^3 m^{-2} s^{-1}$	Reference
6.4 mm alfalfa pellets	0.0091	0.6050	0.005-0.820	Sokhansanj et al. (1993)
6.7 mm feed pellets	0.0025	0.8116	0.009-0.236	Ray et al. (2003)
28 mm long cut willow chips	0.0117	0.5852	0.052-0.650	Kristensen and Kofman (2000)
8 mm wood pellets from sawdust	0.0111	0.5917	0.020-0.300	Kristensen et al. (2003)
6.4 mm pellets (mixed sizes)	0.0112	0.5482	0.010-0.800	This study

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CHAPTER 3[2]

LOW AIRFLOW PERMEABILITY OF WOOD PELLETS

3-1. Introduction

Currently, most wood pellets in Canada are made from compacted sawdust, a by-product of saw mill operations. A typical pellet diameter is 6 mm, its length varies up to 30 mm. Pellets are dense with a single particle density of about 1.2 g/cm^3. The bulk density of pellets range from 600 to 750 kg m^{-3}. Their high density permits compact storage and low cost transport over long distance. The moisture content of pellets is in the range of 5-7% wet mass basis (w.b.). Design of cooling and aeration systems for wood pellets storage is based on pressure drop versus air velocity relationships (Giner and Denisienia, 1995).

Several factors affect the resistance of bulk granulated biomass to airflow including the air viscosity and density, porosity of the bulk material, orientation of the particles in bulk, size, and shape and particle surface condition. Brooker et al. (1974), Haque et al. (1978), Hukill and Ives (1955), Sokhansanj et al. (1993), Al-Yahya and Moghazi (1998), Bakker-Arkema et al. (1969), Gunasekaran et al. (1983), Henderson (1943), Montross (2005) and Siebenmorgen and Jindal (1987) have developed airflow resistance evaluations in test apparatus with circular cross−sections bin shapes. A few researchers used test bins with square (Gunasekaran and Jackson, 1988; Shedd, 1953; Hellevang et al., 2001) or rectangular cross−sections (Kumar and Muir, 1986). The effect of bin cross section on the airflow resistance measurements was also investigated (Ray et al. 2004). The results indicated that the test apparatus cross section had no effect on the measured airflow resistance.

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[2] A version of this chapter will be submitted for publication. Yazdanpanah, F., Sokhansanj, S., Lau, A., Lim, C.J., Bi, X., Melin, S. Low Airflow Permeability of Wood Pellets.

ASAE D272.3 (2007) provides data on airflow vs. pressure drop for about 40 mostly agricultural crops, including alfalfa cubes and pellets (Sokhansanj et al. 1993). Shedd (1953) used the following equation to express the pressure drop airflow data for grains and seeds

$$V = a_1(\Delta P)^{b1} \tag{1}$$

where V is the air superficial velocity, ΔP is the pressure drop and a_1 and b_1 are constants. Hukill and Ives (1955) suggested the following equation to relate airflow to pressure drop in agricultural materials.

$$\frac{\Delta P}{L} = \frac{a_2 V^2}{\ln(1 + b_2 V)} \tag{2}$$

where ΔP is the pressure drop (Pa), L is the depth of the bed (m), V is superficial (frontal) air velocity (m s^{-1}). Constants a and b are tabulated in the ASAE D272. Ergun (1952) divided the flow regime in a porous packed bed to viscous and turbulent flows and used the following equation to represent these two flow regimes.

$$\frac{\Delta P}{L} = a_3 V + b_3 V^2 \tag{3}$$

where a_3 and b_3 are coefficients associated with viscous flow and turbulent (dynamic) flow,

$$a_3 = 150 \frac{(1 - \varepsilon)^2}{\varepsilon^3 \phi^2} \frac{\mu}{d^2} \tag{4}$$

$$b_3 = 1.75 \frac{(1 - \varepsilon)}{\phi \varepsilon^3 d} \rho \tag{5}$$

Bed parameters are porosity ε (fraction), bulk density ρ (kg m^{-3}); equivalent diameter of bed particles d (m); acceleration due to gravity, and viscosity of the air fluid μ (Pa s) and the shape factor (ϕ).

The moisture content during ventilation, storage, and handling influences packing characteristics and thus, affects the resistance to airflow in bed. The effects that moisture content has on pressure drop in beds of alfalfa pellets were formulated by Sokhansanj et al. (1993). The specified airflow range for alfalfa pellets was 0.0053 to 0.82 m s^{-1}. No other recent data are available in the literature on airflow versus pressure drop in pelleted biomass for low air flow range.

The objectives of this study were (1) to determine the permeability to low air flow of bulk wood pellets, (2) to investigate the effect of moisture content on the static pressure drop and (3) to evaluate equations that relate differential static pressures in beds of bulk wood pellets subject to forced airflow. The tests were accompanied with measuring physical properties of the tested pellets.

3-2. Materials and methods

3-2-1. Materials

Three different types of fuel wood pellets from three wood pellet processing plants in BC were used. All of these pellets were made from saw dust with no bark content. The pellets varied in dimensions, moisture content, bulk density, particle density and durability. Pellet length and diameter were measured using electronic calliper for 200 pellets. Density of a pellet was calculated from its volume and mass. The moisture content of the pellets were measured by oven drying at 103°C for 24 hours or until there was no further change in weight. The moisture content is expressed in wet basis (ASAE S358.2). The measurements were made in triplicate.

Bulk density of wood pellets was determined according to a slight modification of ASAE Standard ASAE S358.2. A cylindrical container 152 mm in diameter and 122 mm in height was used. Wood pellets were poured slowly into the bucket from a height of 500 mm from the bottom of the container until the container was overflowing. Excess material was removed by striking a straight edge across the top. The weight of the material with the container was recorded to 0.01 g precision. For tapped density, the loosely filled container was tapped on the laboratory bench 5 times. Filling and tapping was repeated until the container was overflowing. The filled container was weighed to 0.01 g precision. The net weight of the samples was obtained by subtracting the weight of the empty bucket.

The bulk porosity or void space in bed was determined using the following equation (Mohsenin, 1986):

$$\varepsilon = 1 - \frac{\rho_b}{\rho_d} \tag{6}$$

where ρ_b is the bulk density and ρ_d is the single particle density of wood pellet. The durability of pellets was measured using DURAL Tester [Sokhansanj et al., 1999]. The tester uses 100 g sample subjected to a rotating knife in a sealed container for 30 s. The treated sample was sieved through a 4 mm wire mesh sieve. Overs and unders were weighed and their percent mass of the original sample mass was expressed as breakage.

3-2-2. Methods

Experimental apparatus for airflow-pressure measurement consisted of a transparent acrylic cylindrical pellet container and instruments for measuring the flow rates and static pressure (Figure 3.1). The container was 290 mm in diameter and 570 mm in height. The container height was extended to 1140 mm for low airflow measurements. A plenum that contained plastic rings provided for uniform entry of air into the container. The source of air was from the centralized compressed air generating station.

Air was filtered before entering the container. The air flow from the compressed air line passed through a series of filters, pressure regulators and through the float-type airflow meter before entering the pellet column. The static pressure was measured 50 mm from the bottom of the cylinder. Four float in-line flow meters were used to provide measurements of a wide range of airflow.

The first two flow meters were used for tests on measuring low flow rates (0.0002 to 0.0220 m s^{-1}) and the latter three flow meters together (0.0066 to 0.4646 m s^{-1}) were used to test and compare the pressure drop along the bed on three different sides and also for tests on moisture content. Table 3.1 lists the flow meter models and the measurement ranges. Air pressure was measured using an inclined manometer and two digital manometers. Table 3.1 lists the flow meter and manometer models and the range of measurements. Four pressure taps were located at four levels 100 mm apart along the height of the column.

Air was induced from low flow. Pressure drop was measured through beds of wood pellets at air flow rate from 0.0002 to 0.0220 m s^{-1}. The experiments for the air flow rate and moisture content were done with clean sieved wood pellets.

All tests in this study were conducted in three replicates. For low air flow range (0.0002 to 0.0220 m s^{-1}) pressure drop was measured at 25 levels of airflow rates. The ambient temperature and pressure were recorded during each test.

3-3. Results and discussion

Table 3.2 shows the physical properties of the sample used for the tests of low permeability. The sample used was a mixture of sizes (diameter 5.9 to 26.4 mm) with low moisture content (2.8%). The original bags of pellets contained 1.4 % of fines. The fine is defined as particles that pass through 4 mm wire mesh screen. The wall effect on pressure drop measurement was neglected. According to Carman (1937), these effects on the overall pressure drop in the bed can be neglected if the diameter of the bed is greater than 10 times the diameter of the spherical particles in the column. As the materials in the bed are not spherical, based on the Geankoplis (1993), the ratio of the diameter of the column of packed materials to the effective particle diameter should be a minimum of 8:1 to 10:1 for wall effects to be small. Geankoplis (1993) proposed the effective particle diameter to be calculated by:

$$D_p = \frac{6}{a_v} \qquad (7)$$

where a_v is the specific surface area of a particle in m^2/m^3. It is obtained by dividing the surface area of a particle by its volume. For a pellet 6 mm in diameter and 12 mm length the specific area is 0.75 and D=8 mm. The required diameter of the container should be at least 80 mm. The container used for bulk density measurement has a diameter of 290 mm.

Table 3.3 shows the properties of the samples used in tests on moisture content. The samples used had almost the same size distribution while their moisture content was significantly different. As shown in figure 3.2, the size distribution of sample 1 (MC = 5.4%) and sample 2 (MC = 8.1%) are almost the same and just slightly higher than that of sample 3 with MC = 2.8%. The pellet with 8.1% moisture content seemed to have lower resistance to air flow.

Figures 3.3 show a log-log plot of pressure drop versus air flow for wood pellets. The flow rates used ranged from 0.0002 to 0.0220 m s^{-1}. The plotted data on log-log scale are linear. In this sample, for a bulk pellet of mixed sizes where pellet length ranges from 6 mm to 26.4 mm, the pressure drop started from 0.18 Pa/m and went up to 8.30 Pa m^{-1}.

Figure 3.4 shows the air flow pressure drop data for three types of pellets. As all pellets are all mixes of sizes and their size distributions and bulk densities are almost the same, it can be concluded that the slight decrease in pressure drop with increasing air flow was due to an increase in moisture content. Similar to agricultural grains, the higher the moisture content is, the lower the pressure drop is (Chung et al., Giner et al., Pagano et al., Montross et al., Li et al. and Sacilik et al.). Although the three samples used are not the same samples, their size distribution and bulk densities are very close. Results from previous experiments (Chapter 2) to determine the relationship between bulk density and pressure drop show that 30-35% changes in the bulk density would change the airflow resistance by 20-25%. The bulk densities of the samples used in these test differ by about 5%, while the differences in pressure drops among the three treatments exceeds 30%. Therefore, it may be concluded that the differences in pressure drops are due to the different moisture contents of the material. Moreover, aside from particle size/bulk density, other factors such as bed porosity, surface roughness of the pellets and the porosity of the pellet itself could have affected the pressure drop somewhat.

All the air flow pressure drop measurements have been done on one side of the column (circular bed) up to now. To assess the possible symmetry in pressure drop data in the column, measurements were then made on three sides of the bed - left, right and front. The air flow range was split up into two ranges - 0.0023 to 0.02200 m s^{-1} (low airflow range) and 0.0142 to 0.7148 m s^{-1} (high airflow range) and the pressure drop data were compared. Results from these measurements show that pressure drops were essentially the same along the bed of wood pellets on all sides. For the low airflow range, all three sets of measurements follow a linear trend, and for the high range of air flow they all lie in the same quadratic graph.

Some factors which affect the quality (moisture content, durability and size distribution) of pellets can subsequently affect on the resistance of material to air flow. As mentioned by Lehtikangas et al., (2000) storage of such pelletised materials would affect the properties of the material. The average pellet length was decreased due to breakage during storage. Storage for long period seemed to have negative effect on durability of pellets but the average bulk density or the density of individual pellets did not change significantly during storage. Moreover high moisture pellets could promote microbial growth and all kinds of pellets have a tendency to obtain equilibrium moisture content during storage.

In all tests the bed porosity varied between 0.3 to 0.4. The single pellet porosity was about 0.10 and up to a maximum of 0.29. Comparing the values of the pellet porosity and the bed porosity, it is found that the single pellet porosity itself is not so low to be neglected in calculating the resistance to airflow and is significantly notable.

Three airflow versus pressure drop equations 1, 2 and 3 were fitted to the entire range of experimental data. Non-linear least squares regression method with two software packages (DataFit 8.2, Oakdale Engineering; Polymath 6.0 (2004)) was used. Table 3.4 contains values of fitted parameters, their standard errors, and standard deviation of estimates (S_y). S_y expresses the average deviation between experimental and predicted values and is defined is as follows:

$$S_y = \left(\frac{\sum_{i=1}^{N}(\text{predicted}_i - \text{experimental}_i)^2}{(N-2)}\right)^{\left(\frac{1}{2}\right)} \quad (8)$$

where N is the number of data points and (N-2) is the number of degrees of freedom.

For the flow rate range 0.00012 to 0.7148 m s^{-1}, the average S_y in equation 1 was 8.41 Pa m^{-1}. This value for equation 2.0 was 7.39 Pa m^{-1}. Equation 3 fitted data better than the other two equations with the average S_y of 7.12 Pa m^{-1}.

Table 3.5 lists fitted parameters to Shedd's equation for different materials including alfalfa pellets, feed pellets, 28mm cut willows and 8mm wood pellets. The fitted parameters for this study are much closer to the results for 28mm cut willows from Kristensen and Kofman than those of 6.4 mm alfalfa pellets and 6.7mm feed pellets, although the air flow rate used in this study is much broader than the other researches in the table. To be able to observe how our selected equations predict the entire range of air flow rate, the error percentage of pressure drop prediction was calculated as a function of airflow rate.

$$\text{Relative Error} = 100\frac{(\text{predicted}_i - \text{experimental}_i)}{\text{experimental}_i} \qquad (9)$$

Figure 3.5 shows that equation 2 and equation 3 had a lower error at low airflows and had a better fit to the entire range of flow rate (The whole range of flow rate covered by four flow meters was used for model fitting and error calculation (0.0002 to 0.6791 m s^{-1}). Ergun equation covers viscous (laminar flow) and turbulent flow regimes and it seems to explain the data best. The flexibility of the Ergun-type equation [model 3, Eqn 3.] can be described to its two-term nature, which reflects the transition from laminar flow (linear term) to fully turbulent flow (quadratic term).

3-4. Conclusion

The resistance of wood pellets was measured as a function of wood pellet moisture content and the column side on which the pressure drop measurement was done. The low airflow permeability was also investigated. The data were fitted into Shedd, Hukill and Ives and Ergun type model to see how well they behaves and difference between the calculated pressure drop and experimental pressure drop shows a quite good fit with the Hukill and Ives model and a better one with the Ergun Model. The tests on moisture content of pellets shows a slight decrease in the resistance as the moisture content increases. Measurements on different sides of bed seems the same pressure drop and showing that the pressure drop along the column is the same.

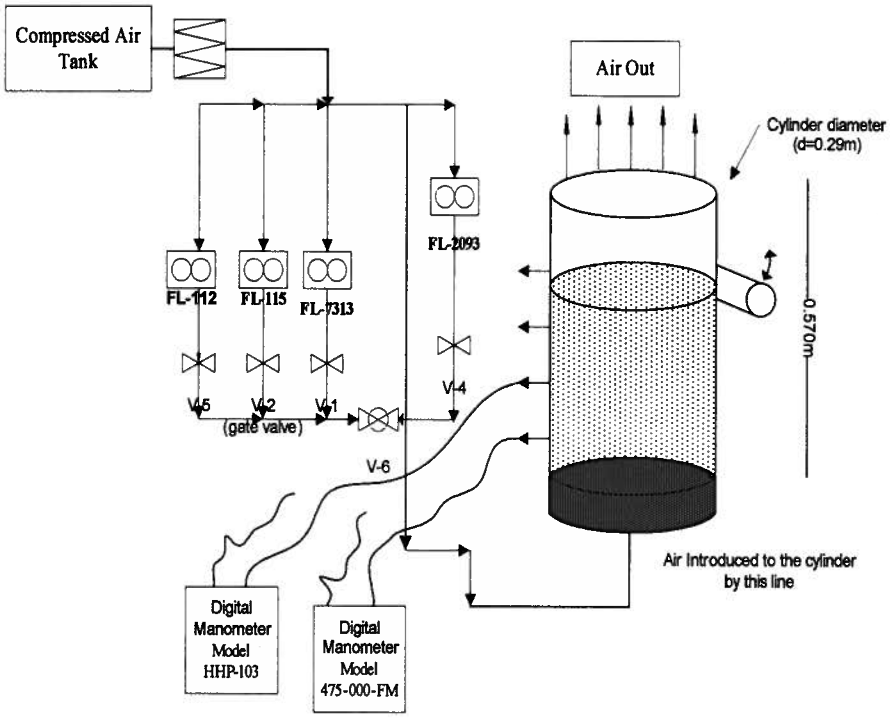

Figure 3.1 Equipment for measuring the resistance of wood pellets to air flows.

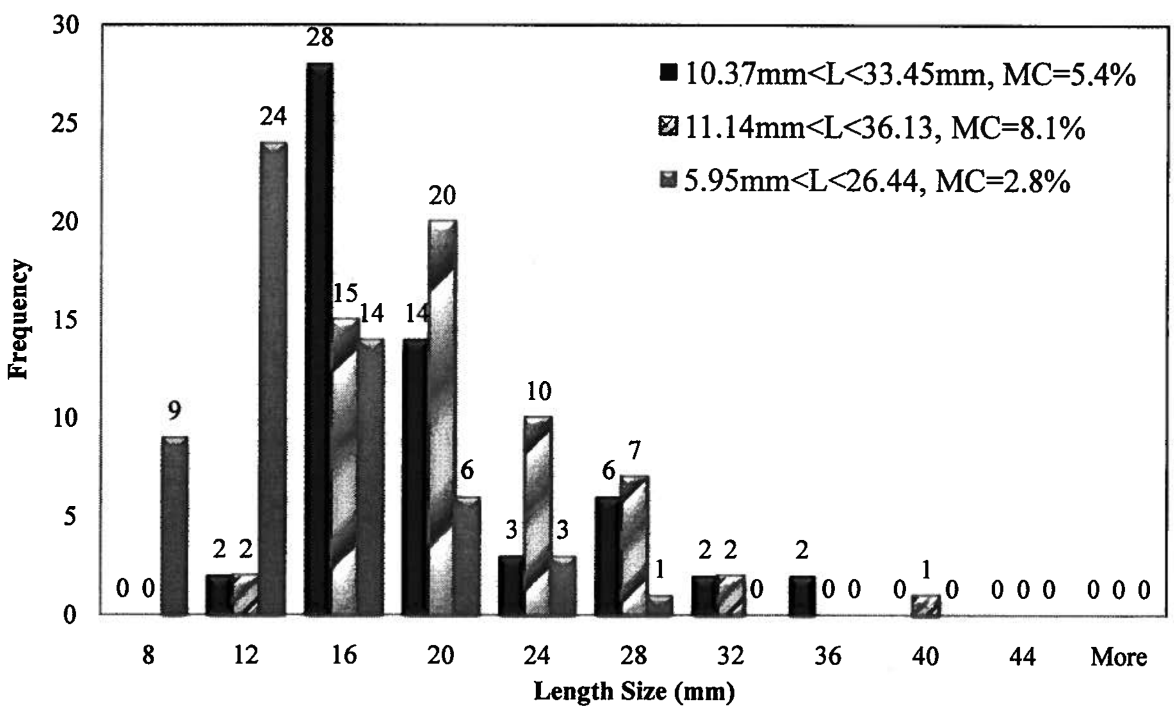

Figure 3.2 Size Distribution for Samples 1, 2 and 3 in moisture content tests

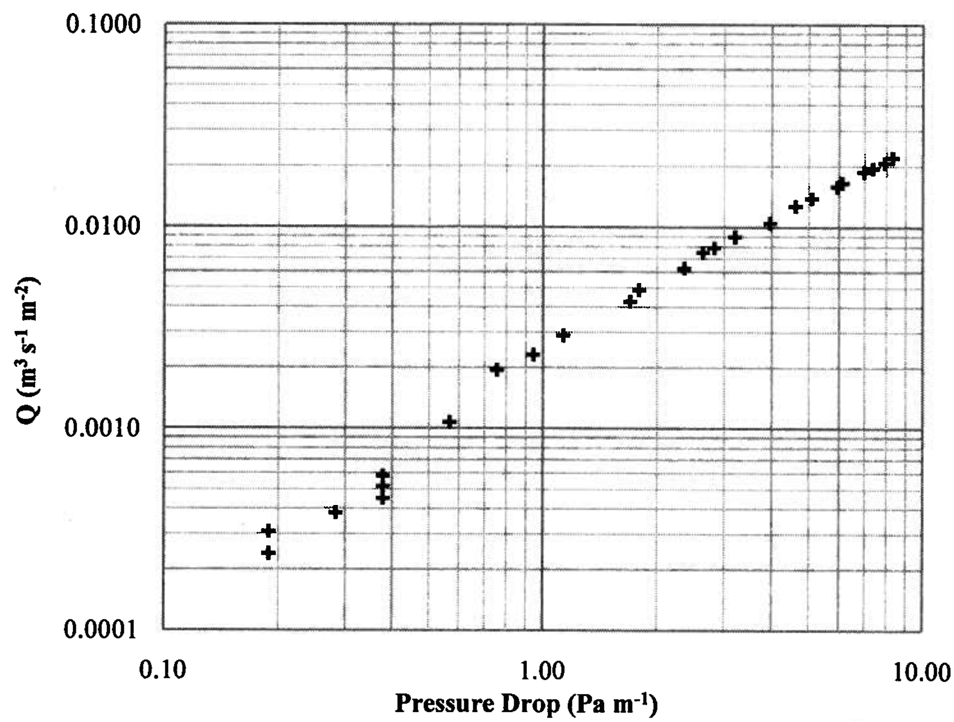

Figure 3.3 Resistance of a mix of wood pellets to very low airflow

(Flowrate from 0.0002 to 0.0220 m s^{-1})

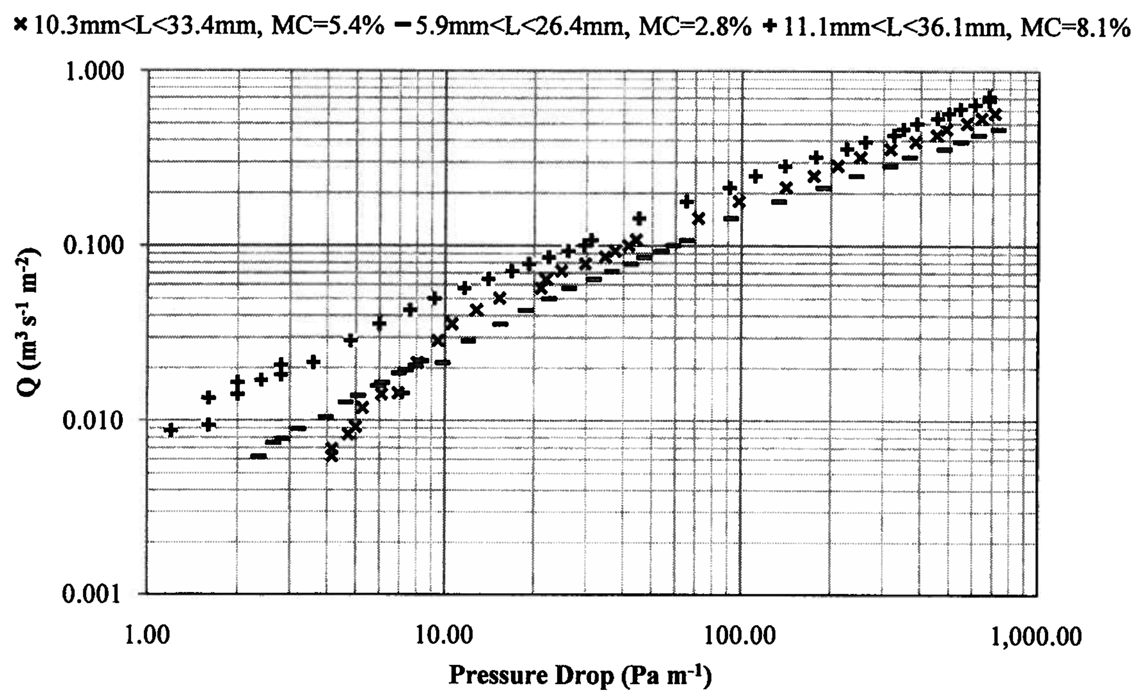

Figure 3.4 Experimental pressure drop per unit depth of bed height as a function of air flow for three different moisture content (Particle size range was between 5.9mm to 36.1)

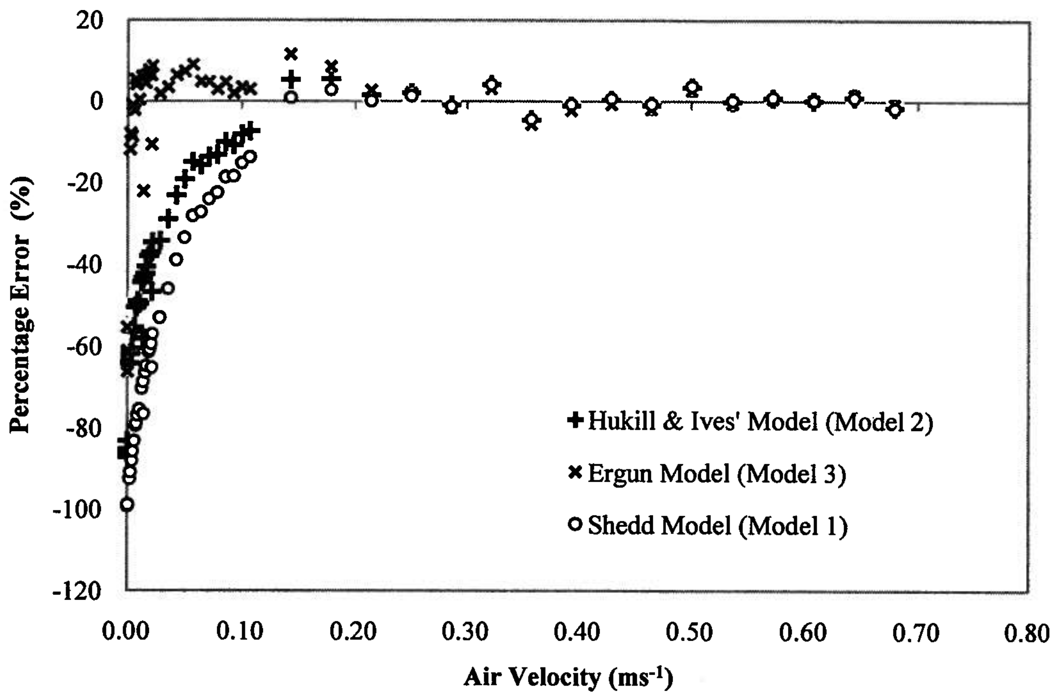

Figure 3.5 Percentage error in the prediction of pressure drop as function of air velocity for 3 models: (1) Shedd-type model (2) Hukill and Ives model (3) Ergun-type model

Table 3.1 Flow meters and manometers model and measurement ranges

Flow Meter Type	Air flow range
FL-112	0.00011 to 0.00058 m s^{-1}
FL-115	0.00044 to 0.02200 m s^{-1}
FL-7313	0.0142 to 0.1072 m s^{-1}
FL-2093	0.1072 to 0.7148 m s^{-1}

*All flow meters from Omega engineering Inc. and Accuracy ±2% full scale

Manometer Type	Pressure difference range
Model 26 Mark II	0 to 1743.574 Pa
Model HHP-103	0 to 2953 Pa
Model 475-000-FM	0 to 249.1 Pa

*Type 26 Mark II and 475-000-FM were from Dwyer Instrument Inc. and HHP-103 from Omega Engineering Inc.

Table 3.2 Properties of wood pellets used in low permeability test

Physical Property	Sample
Diameter (mm)	6.2[a] (5.8 – 6.4)[b]
Length (mm)	12.6 (5.9 – 26.4)
Moisture content (%)	2.8 (2.7-2.8)
Loose bulk density (kg m^{-3})	720
Particle density (g cm^{-3})	1.27 (1.08-1.35)
Bed Porosity (ε)	0.43
Durability	69.20

[a] mean value; [b] range of values

Table 3.3 Pellet properties of samples used in tests on moisture content*

Sample	MC %	Bulk density (kg m^{-3})	Durability (%)	Length (mm)	Diameter (mm)
Sample 1	8.1	757	53.60	19.0 (11.1–36.1)	6.3 (3.3-6.8)
Sample 2	2.8	720	69.20	12.0 (5.9-26.4)	6.2 (5.8-6.4)
Sample 3	5.4	761	56.12	17.5 (10.3-33.4)	6.3 (6.0-6.6)

*Values in parenthesis show the range of data and values outside parenthesis show the mean

Table 3.4 Estimated constants for Shedd (Eq.1), Hukill-Ives (Eq.2), and Ergun (Eq. 3).

Air Flow Range	a_i	b_i	Standard Error		S_y
			a_i	b_i	
0.00011 to 0.7148 m s^{-1}	0.0105	0.5740	0.0002	0.0039	8.41
0.00011 to 0.7148 m s^{-1}	12800	97.35	511	15.7	7.39
0.00011 to 0.7148 m s^{-1}	353	2550	14.7	27.5	7.12

Subscript i is index, i=1 Shedd, i=2 Hukill-Ives, i=3 (Ergun)

Table 3.5 Constants a_1 and b_1 in Shedd's equation among various materials.

Product	a_1	b_1	Airflow range $m^3 s^{-1} m^{-2}$	Reference
6.4 mm pellets	0.0091	0.6050	0.0005 to 0.820	Sokhansanj et al. (1993)
6.7 mm pellet	0.0025	0.8116	0.009 to 0.236	Ray et al. (2003)
28 mm long cuts of willow	0.0117	0.5852	0.052 to 0.650	Kristensen and Kofman (2000)
8 mm wood pellets from saw dust	0.0111	0.5917	0.02 to 0.2	Kristensen et al. (2003)
6.4 mm pellets (mixed sizes)	0.0105	0.5740	0.00011 to 0.7148	This study

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CHAPTER 4[3]

PERMEABILITY OF WOOD PELLETS IN THE PRESENCE OF FINES

4-1. Introduction

Fine materials are continuously produced during drying, transporting and handling of wood pellets. Pellets mixed with broken and fine materials increases variation in resistance to airflow in a fixed bed of pellets causing uneven temperature and moisture in an aerated bin. The resulting localized high moisture or high temperature conditions may lead to heating and spontaneous combustion.

Graphical data on airflow vs. pressure drop are available in ASAE D272.3 (ASABE 2007) for about 40 mostly agricultural crops and products including for alfalfa cubes and pellets. The graphical presentation is accompanied by Hukill and Ives (1955) equation.

$$\frac{\Delta P}{L} = \frac{a_2 V^2}{\ln(1 + b_2 V)} \tag{1}$$

where ΔP is the pressure drop (Pa), L is the thickness of the bed (m), V is superficial (frontal) air velocity (m s^{-1}). Constants a and b for clean grains and products are tabulated in the ASAE D272. For the effect of fines on resistance to airflow of shelled corn, ASAE D272 recommends equation (2) to account for the fraction of fine content in a bed of granular material.

$$\left(\frac{\Delta P}{L}\right)_{corrected} = \left(\frac{\Delta P}{L}\right)_{clean} (1 + kf) \tag{2}$$

[3] A version of this chapter will be submitted for publication. Yazdanpanah, F., Sokhansanj, S., Lau, A., Lim, C.J., Bi, X., Melin, S. Permeability of Wood Pellets in the Presence of Fines.

where f is the fraction fine content in the mix. ASAE D272 gives an estimation of f as a function of airflow for shelled corn.

Jayas et al. (1990) developed data on airflow-pressure drop for fine content in beds of canola grain. Similar studies were conducted by Sokhansanj et al. (1993) for alfalfa pellets and Li et al. (1994) for bulk grains. Haque et al. (1978) in studying airflow resistance of corn mixed with fines. Giner and Denisienia (1995) showed a relation between pressure drop and air flow to have to constants of k_1 and k_2 as:

$$\frac{(\frac{\Delta P}{L})_{corrected}}{(\frac{\Delta P}{L})_{clean}} = k_1 + k_2 f \quad (3)$$

The objectives of this study were to (1) develop experimental data on permeability of bulk wood pellets to air flow in the presence of fines, and (2) to develop an equation to predict pressure drop as a function of airflow rate and fines content.

4-2. Materials and methods

4-2-1. Materials

Pellets were received in 30 kg bags from a commercial pellet producer in British Columbia. Pellets had been made from saw dust from heart wood (no bark). The moisture content of pellets was 2.8% (wet mass basis) measured according to the ASAE S358.2 (ASABE 2006) standard procedure. To prepare samples for airflow test, the contents of each bag were sieved for 5 minutes over a 4 mm wire mesh screen on a vertical Gilson TM-5 shaker. The materials left on the screen were designated "clean pellets". The materials passed through the screen were designated as "fines". A sample of clean pellets and fines were analyzed through a 5-sieve Tyler Rototap according to the ASAE Standard S319.3 (ASABE 2007).

Bulk density of wood pellets was determined according to a slight modification of ASAE Standard S269.4 (ASAE 2007). A cylindrical container 152.4 mm in diameter and 122 mm in height was used. Wood pellets were poured slowly into the bucket from a height of 500 mm from the bottom of the container until the container was overflowing. Excess material was removed by striking a straight edge across the top. The weight of the material with the bucket was recorded to 0.01 g precision. For tapped density, the loosely filled container was tapped on the laboratory bench 5 times. Filling and tapping was repeated until the container was overflowing. The filled container was weighed to 0.01 g precision. The net weight of the samples was obtained by subtracting the weight of the empty bucket.

The durability of pellets was measured using DURAL Tester (Sokhansanj et al. 1999). The tester uses 100 g sample subjected to a rotating knife in a sealed container for 30 seconds. The treated sample was sieved through a 4 mm wire mesh sieve. Overs and unders were weighed and their percent mass of the original sample mass was expressed as breakage.

Six mixing ratios of pellets and fines at 0%, 1%, 5%, 10%, 15 and 20% (w/w) were planned for the experiment. Roughly 20 kg biomass was needed to fill up the container. Test mixtures were prepared in small batches about 2 kg each. For instance a 2 kg of 10% mixture was prepared by mixing 200 g fines with 1800 g clean pellets. Mixing was done in a plastic container using a piece of wood stick as stirrer. A complete mixing was judged visually. Ten 2-kg batches were prepared to make up the 20-kg column. Each mixture was poured into the test column, evened out and more layers were added until the desired level was reached. The bulk density (total mass in the test column divided by volume) for each mixture was recorded.

Density of a pellet was calculated from its volume and mass. A manual calliper was used to measure the diameter and length of 200 randomly selected pellets from the cleaned batch. The moisture content of the pellets were measured by oven drying at 103 °C for 24 hours or until there was no further change in weight. The moisture content is expressed in wet basis (ASAE S358.2). The measurements were made in triplicate.

4-2-2. Experimental apparatus

Experimental apparatus consisted of a transparent acrylic cylindrical pellet container and instruments for measuring the flow rates and static pressure (Figure 4.1). The container was 290 mm in diameter and 570 mm in height. The container was made of two sections, a plenum filled with plastic rings and the sample holder. A screen at the bottom separated sample holder from plenum. The source of air was from the University centralized compressed air generating station. Air was filtered before entering the container. Four float in-line flow meters were used to cover a wide range of flow rates. Table 4.1 shows the flow meters model and airflows used in these sets of tests. Air pressure was measured along the depth of wood pellets column by using a digital manometers. Table 4.1 lists the model and range of manometers used. Four pressure taps were located at four levels 100 mm apart along the height of the column. The static pressure was measured 50 mm from the bottom of the cylinder.

4-2-3. Test procedure

Once the container was filled with the test material, air was allowed to flow into the plenum and through the column. Each test was done by loading the test column with semi-packed fill. This was achieved by pouring the pellets from the height of about 0.5 m into the column of the bed gradually. This was not a fully packed fill since the material was not poured from a greater height as was done by Jayas et al. (1989), and settling was not induced after each increment of fill as was done by Beavers et al. (1973). The flow of air was started from low end. The flow was increased by manipulating a manual valve until the float in the flow meter stabilized. Pressure drop was measured in approximately 50 airflow intervals. The air flow ranged from 0.004 to 0.357 m s^{-1}. Measurements were repeated by filling the column with the same sample three times.

4-3. Results and discussion

Table 4.2 shows the physical properties of wood pellets with a nominal diameter of 6.2 mm and a length of 12.6 mm. The sample used was a mixture of sizes, diameter varying from 5.8 to 6.4 mm and length varying from 5.9 to 26.4 mm. The moisture content of these samples at the time of test was low at 2.8%. The original bags of pellets contained 1.4% of fines (particles passed through a 4 mm wire mesh screen). Figure 4.2 shows the size distribution of fines. More than half of the particles that passed through 4 mm screen as fines were larger than 2 mm. About 20% of the materials were less than 0.6 mm in size. The geometric mean diameter of particles was 0.75 mm. The standard deviation of the particles was 0.57 mm. Bulk density of material in the testing column was 720 kg/m^3 ($\pm$3 kg/m^3) and decreased by adding fines. Figure 4.3 shows the change in bulk density versus fine percent. Small vertical error bars in the graph indicates that the standard errors were so small.

Figure 4.4 shows the pressure drop vs. air velocity data for 6 samples used in tests of fine material effect. The pressure drop increased with increasing the fine content and the curves were almost parallel on the log-log scale. The pressure drop increased 50-80% times when fines percent was increased from 0 to 10% on a linear scale. The pressure drop increased 3-6 times when the percent fines increased from 0% to 20%.

The wall effect on pressure drop measurement can be neglected according to Carman (1937), provided the diameter of the bed is greater than 10 times the diameter of the spherical particles in the column. For non spherical particles the ratio of the diameter of the column of packed bed to the effective particle diameter should be a minimum of 8:1 to 10:1 for wall effects to be negligible. Geankoplis (1993) defines the effective particle diameter as,

$$D_p = \frac{6}{a_v} \tag{4}$$

where a_v is the specific surface area of a particle in m^2/m^3 and is obtained by dividing the surface area of a particle to its volume. For clean wood pellets *Dp* ranges from 0.007 to 0.008 and the ratio of the column diameter to particle diameter is 34 to 39. Therefore we can neglect the wall effect.

Hukill and Ives equation was fitted to experimental data using non-linear least squares regression using two software packages (DataFit 8.2, Oakdale Engineering; Polymath 6.0 (2004)). Table 4.3 lists estimated a_l and b_l and their standard errors and correlation coefficients. The Hukill and Ives equation for clean pellets is:

$$\frac{\Delta P}{L} = \frac{5180Q^2}{\ln(1 + 19.05Q)} \tag{5}$$

where $(\Delta P)_{clean}$ is pressure drop in Pa m^{-1} and Q is airflow in m^3 s^{-1} of volume flow per m^2 of the frontal area. Figure 4.5 shows also the plot of equation 5 over the entire range of airflow.

Table 4.3 lists the estimated values of a_1 and b_1 as fines content increases. The estimated a_1 increases with increased fines content. The estimated values for b_1 do not show any trend. The value of b_1 was fixed at 19.05 for clean pellets and estimated new values of a_1 as a function of fines content,

$$a_1 = 5180\,(0.83 + 20.7f) \qquad R^2 = 0.98 \tag{6}$$

Equation 6 is similar to Jayas's equation 3. The intercept was set to y=1 at x=0 to develop the following equation similar to equation 2,

$$a_1 = 5180\,(1 + 19.6f) \qquad R^2 = 0.97 \tag{7}$$

where f is the fines content in decimal fraction. Figure 4.4 shows the predicted pressure drop using equation 7. The fit is not satisfactory. Figure 4.5 shows the predicted pressure drop versus airflow for two fines content. Compared to the experimental values, the fitting is not satisfactory. The constant k needs to be calculated with changes in flow rate to be put in the modified equation for airflow versus pressure drop relationship. The following linear equation of k as a function of airflow was fitted to the data. (Figure 4.6)

$$k = -39.685Q + 23.773 \tag{8}$$

Substituting equation 8 in equation 2 resulted in the following equation among pressure drop, air flow rate and fine material percentage.

$$(\Delta P)_{corrected} = (\Delta P)_{clean}\,[1 + (-39.685Q + 23.773)f] \tag{9}$$

Pressure drop predicted by this equation is close to the experimental data especially in airflow range of 0.004 to 0.103 m s^{-1} (Percent error of 0.003 to 0.011). The results from alfalfa pellets show a linear relation between k and Q values similar to equation 8.

Eqs. (1) and (9) were fitted to the experimental data for wood pellets mixed with 1% fines using a non-linear least squares regression method with software package - DataFit 8.2 (Oakdale Engineering). Deviation of estimates (S_y) was calculated for both equation predictions. S_y expresses the average deviation between experimental and predicted values and is defined as follows:

$$S_y = \left(\frac{\sum_{i=1}^{N}(\text{predicted}_i - \text{experimental}_i)^2}{(N-2)}\right)^{\left(\frac{1}{2}\right)} \tag{10}$$

where N is the number of data points and (N-2) is the number of degrees of freedom.

For the range of flow rates (0.004 to 0.103 m s^{-1}), the average S_y for samples in Eq. (9) was 0.68 Pa m^{-1} respectively, while the corresponding values for Eq. (1) was 1.22 Pa m^{-1}. Eq. (9) fitted the data better than the Hukill and Ives equation with a lower S_y value.

4-4. Conclusion

The resistance of wood pellets to airflow was measured as a function of fine materials in beds of wood pellets. The pressure drop increased with the increase in fine percent. By increasing the fine percent from 0 to about 10%, the pressure drop increased by 50-80% depending on the airflow rate. The pressure drop increased up to 3-6 times of the initial values by increasing the fine materials in bed from 10% to 20%. Hukill-Ives model was fitted to the data to and the equation was corrected for fines content.

Table 4.1 Flow meters and manometers model and measurement ranges

Flow Meter Type	Air flow range
FL-112	0.00011 to 0.00058 m s^{-1}
FL-115	0.00044 to 0.02200 m s^{-1}
FL-7313	0.0142 to 0.1072 m s^{-1}
FL-2093	0.1072 to 0.7148 m s^{-1}

*All flow meters from Omega engineering Inc. and Accuracy ±2% full scale

Manometer Type	Pressure difference range
Model 26 Mark II	0 to 1743.574 Pa
Model HHP-103	0 to 2953 Pa
Model 475-000-FM	0 to 249.1 Pa

*Type 26 Mark II and 475-000-FM were from Dwyer Instrument Inc. and HHP-103 from Omega Engineering Inc.

Table 4.2 Properties of wood pellets used in low permeability test

Physical Property	Sample
Diameter (mm)	6.2[a] (5.8 – 6.4)[b]
Length (mm)	12.6 (5.9 – 26.4)
Moisture content (%)	2.8 (2.7-2.8)
Loose bulk density (kg m^{-3})	720
Particle density (g cm^{-3})	1.27 (1.08-1.35)
Bed Porosity (ε)	0.43
Durability	69.20

[a] mean value; [b] range of values

Table 4.3 Results of fitting Hukill and Ives equation to data

Fine%	a_1	b_1	s.e. (a_1)	s.e. (b_1)	a_1 (b_1=19.05)	s.e.(a_1)
0%	5180	19.05	124.8	0.94	5180	16.79
1%	5206	18.38	213.1	1.38	5306	29.74
5%	8198	15.03	256.1	0.73	9490	40.46
10%	13215	15.42	445.3	1.07	14570	64.17
15%	15236	12.24	288.1	0.44	18824	84.83
20%	25412	16.37	1589.0	2.09	27300	223.25

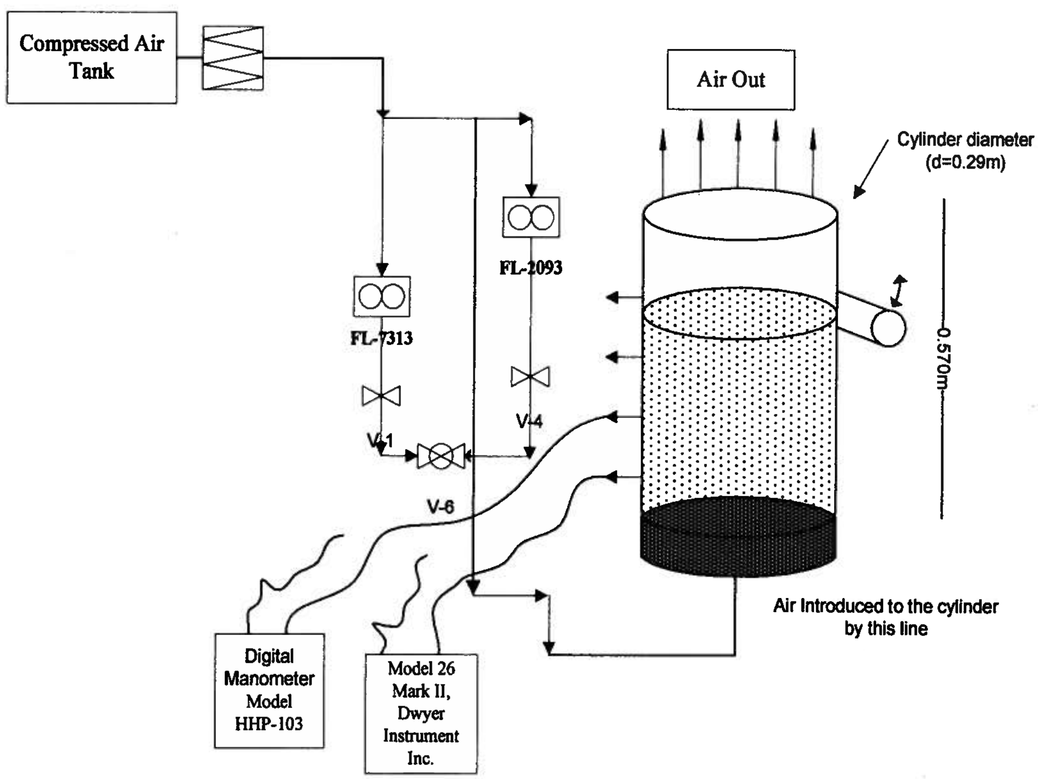

Figure 4.1 Equipment for measuring the resistance of wood pellets to air flows.

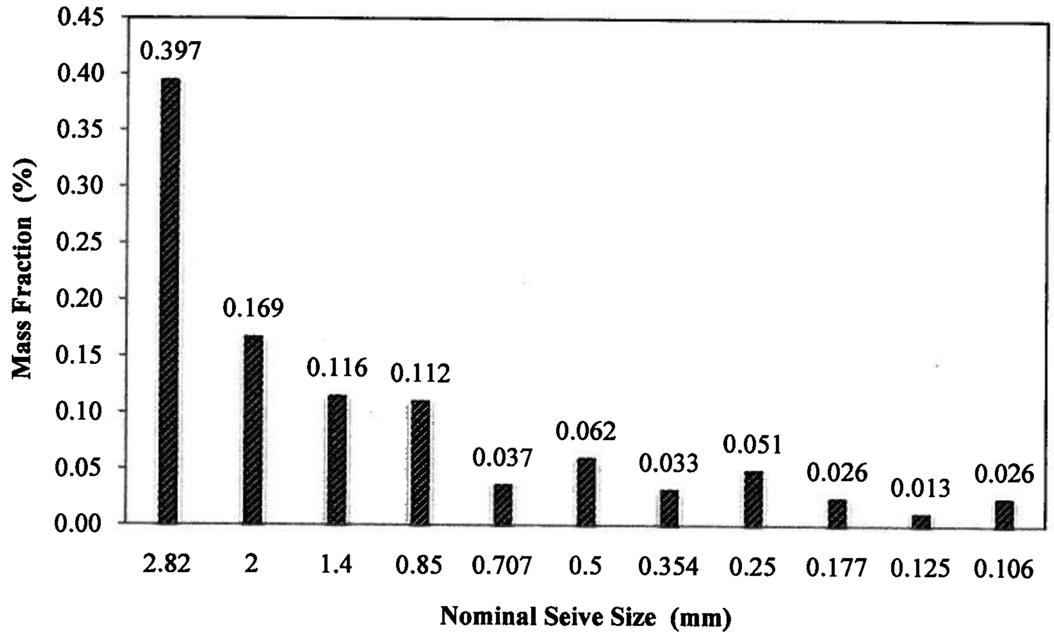

Figure 4.2 Typical particle size distribution of fine materials in bed of wood pellets.

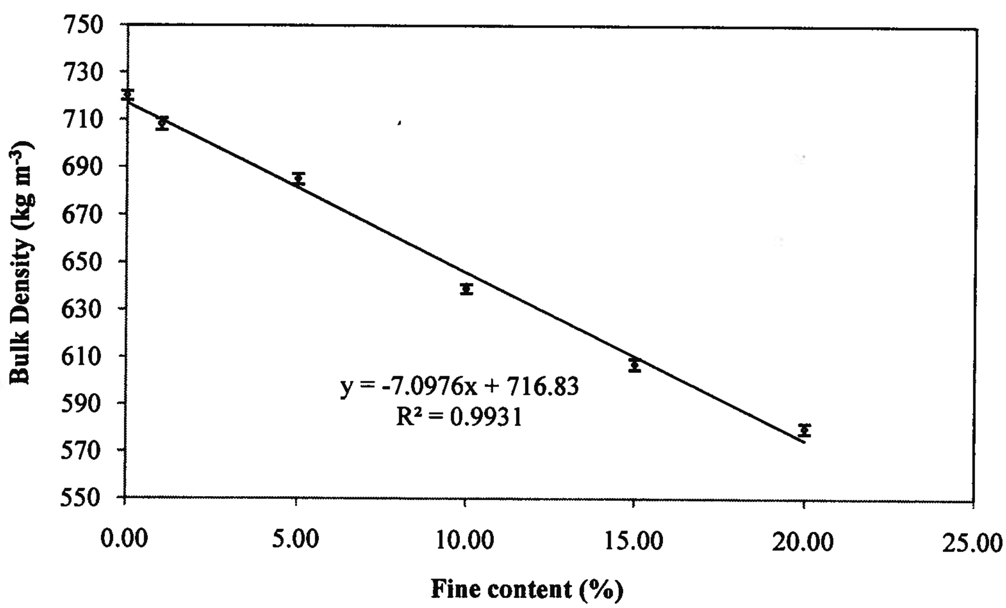

Figure 4.3 Bulk density of wood pellets as a function of fine content.

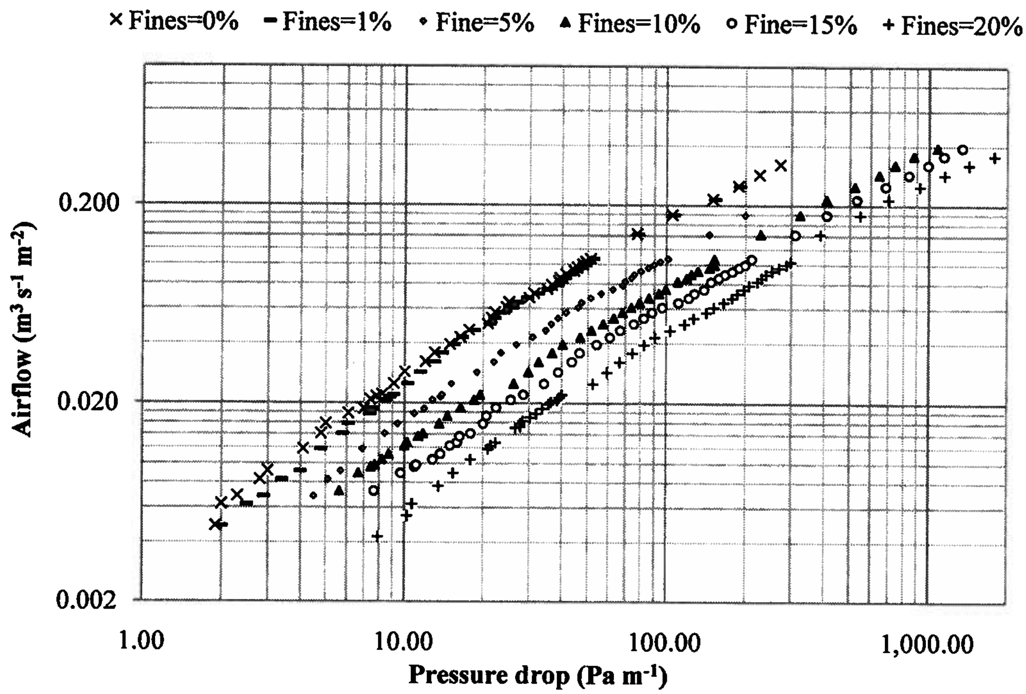

Figure 4.4 Experimental pressure drop per unit depth of bed height as a function of air flow for four different fine contents.

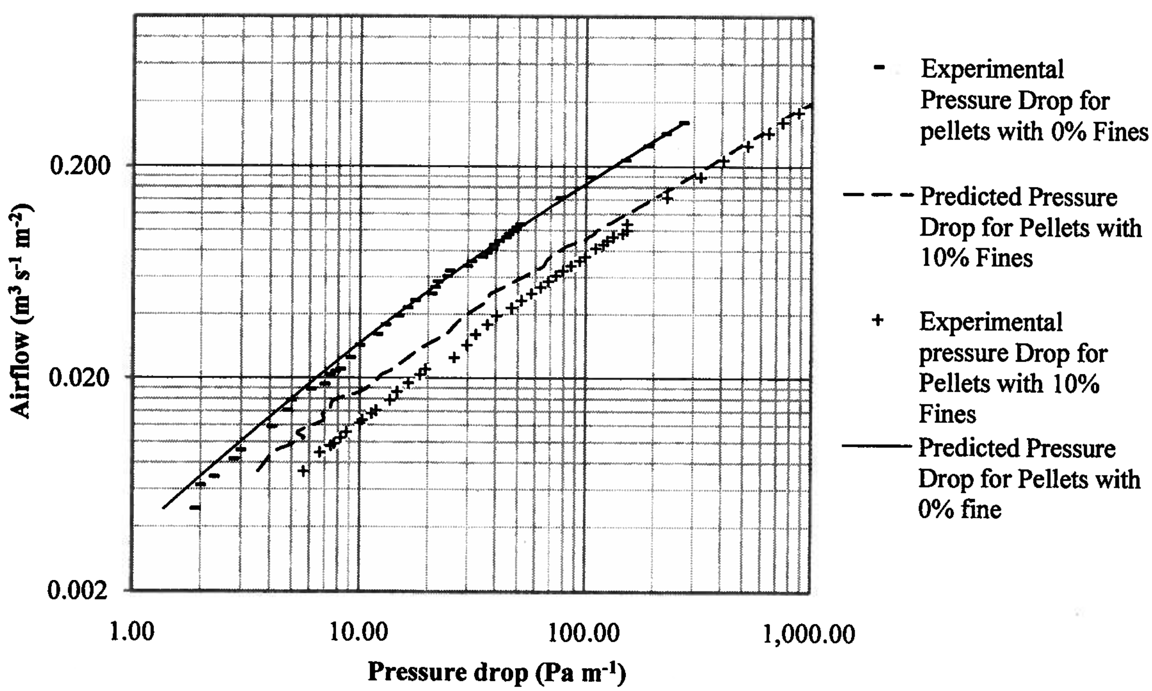

Figure 4.5 Predicted and experimental pressure drop per unit depth of bed height according to Hukil and Ives Equation as a function of air flow for two different fine contents.

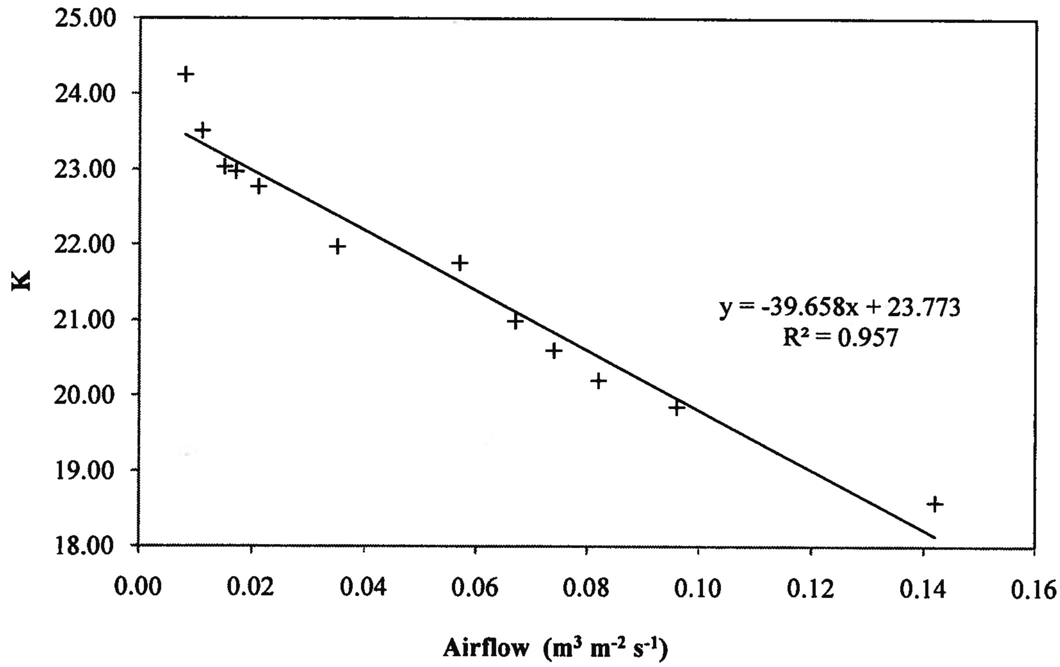

Figure 4.6 Constant k of equation 2 as a function of airflow.

4-5. References

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CHAPTER 5

DISCUSSION, CONCLUSION AND RECOMMENDATION FOR FUTURE WORK

In this study, the permeability to air flow of bulk wood pellets was determined and equations were developed that relate differential static pressures in beds of bulk wood pellets subject to forced airflow. Experimental data on permeability of bulk wood pellets developed for pellets with different moisture content and also for bulk of material in the presence of fine materials and their effects on the static pressure drop was investigated. Equations were developed to predict pressure drop as a function of airflow rate and fines content.

5-1. Discussion and conclusions

Experiments on wood pellets show more resistance from smaller pellets than larger pellets. Mixtures of pellet sizes show less resistance to airflow. This increase in airflow resistance can be described by the availability of larger spaces and more pathways for airflow to pass. For the airflow range of 0.014 to 0.8 m s^{-1}, the maximum pressure drop measured was 2550 Pa m^{-1}. Three models (Shedd, Hukil and Ives and Ergun models) (Hukill and Ives 1955, Shedd 1953 and Erqun 1952) have been fitted to experimental data. An error analysis showed the best fit to the entire data is achieved by Ergun equation.

The effects of other factors such as moisture content of pellets and the presence of fine materials in the bulk of wood pellets on the resistance data were tested. The airflow rate used in these test was from 0.0042 to 0.7148 m s^{-1}. As shown in table 3.3, the 3 types of pellets moisture content were 2.8 %, 5.4% and 8.1% respectively. As the moisture content increased, the pressure drop decreased slightly. Although the three samples used were not the same samples but analyzing their size distribution and comparing their bulk densities, their size distribution and bulk densities were close. Results from experiments on the relationship between the bulk density and pressure drop, show that even 30-35% changes in the bulk density, will change the resistance 20-25%. Comparing the bulk densities of the samples used in these test show that the difference is about 5%,.while the changes in pressure drop data exceeds 30%. It can be concluded that portion of this changes is due to the difference in moisture level of the material.

Chapter 4 presented the results of experiments on the resistance of wood pellets to air flow in the presence of fine materials. The tested airflow range was from 0.004 to 0.357 m s^{-1}.Results from tests show continuous decrease in bulk density of pellets as fine content increases. Due to lower porosity in the bed as a result of fine presence, the pressure drop data shows an increasing trend as fines are added. A range of 3-6 fold increase in pressure drop was measured in beds containing 20% fine material compared when compared to beds of clean wood pellets.

To evaluate the location of pressure taps, the measurements on pressure drop was done on 3 sides of bed at the same level. The air flow range was split up to 2 ranges 0.0023 to 0.0220 m s^{-1} (low airflow range) and 0.0142 to 0.7148 m s^{-1} (high airflow range). The pressure drop data in 3 different sides were compared. No discernible differences between pressure drops were recorded.

Of all major parameters tested in the thesis research experiments, and within the ranges of values tested, airflow rate was found to have the most significant effects, followed by pellets particle size and fines content. Moisture content was found to have the least effect on resistance to airflow.

We used the data on resistance of clean pellets (0% fines) to airflow and divided the airflow range to 3 (Low, middle and high) ranges. Data on each section were fitted to Shedd's equation and correlated *A* and *B* values

Table 5.1. Results of fitting Shedd equation to Q - ΔP data for clean pellets

Airflow Range	A	B	s.e. (A)	s.e. (B)
0.006-0.022 m s^{-1}	3.44×10^{-3}	0.89	2.49×10^{-4}	3.85×10^{-2}
0.024-0.06 m s^{-1}	3.44×10^{-3}	0.90	3.27×10^{-4}	3.18×10^{-2}
0.067-0.178 m s^{-1}	5.27×10^{-3}	0.75	2.26×10^{-4}	1.04×10^{-2}

Table 5.2. Results of fitting Shedd equation to Q - ΔP data for pellets with 1% fines

Airflow Range	A	B	s.e. (A)	s.e. (B)
0.006-0.022 m s^{-1}	2.37×10^{-3}	1.01	1.29×10^{-4}	2.72×10^{-2}
0.024-0.06 m s^{-1}	3.07×10^{-3}	0.92	2.35×10^{-4}	2.51×10^{-2}
0.067-0.178 m s^{-1}	5.06×10^{-3}	0.76	2.32×10^{-4}	1.10×10^{-2}

Table 5.3. Results of fitting Shedd equation to Q - ΔP data for pellets with 5% fines

Airflow Range	A	B	s.e. (A)	s.e. (B)
0.006-0.022 m s^{-1}	1.77×10^{-3}	0.96	1.22×10^{-4}	2.82×10^{-2}
0.024-0.06 m s^{-1}	2.31×10^{-3}	0.85	1.99×10^{-4}	2.38×10^{-2}
0.067-0.178 m s^{-1}	3.65×10^{-3}	0.73	1.32×10^{-4}	7.52×10^{-3}

Table 5.4. Results of fitting Shedd equation to Q - ΔP data for pellets with 10% fines

Airflow Range	A	B	s.e. (A)	s.e. (B)
0.006-0.022 m s^{-1}	1.69×10^{-3}	0.86	3.84×10^{-5}	8.60×10^{-3}
0.024-0.06 m s^{-1}	2.00×10^{-3}	0.79	1.40×10^{-4}	1.71×10^{-2}
0.067-0.178 m s^{-1}	2.67×10^{-3}	0.72	1.37×10^{-4}	8.83×10^{-3}

Table 5.5. Results of fitting Shedd equation to Q - ΔP data for pellets with 15% fines

Airflow Range	A	B	s.e. (A)	s.e. (B)
0.006-0.022 m s^{-1}	1.04×10^{-3}	0.91	9.21×10^{-5}	2.96×10^{-2}
0.024-0.06 m s^{-1}	1.87×10^{-3}	0.75	2.29×10^{-4}	2.80×10^{-2}
0.067-0.178 m s^{-1}	1.54×10^{-3}	0.79	6.02×10^{-5}	7.06×10^{-3}

Table 5.6. Results of fitting Shedd equation to Q - ΔP data for pellets with 20% fines

Airflow Range	A	B	s.e. (A)	s.e. (B)
0.006-0.022 m s^{-1}	6.89×10^{-4}	0.93	2.57×10^{-5}	1.08×10^{-2}
0.024-0.06 m s^{-1}	1.34×10^{-3}	0.75	1.37×10^{-4}	2.13×10^{-2}
0.067-0.178 m s^{-1}	7.14×10^{-4}	0.87	1.01×10^{-4}	2.46×10^{-2}

Tables 5.1 to 5.6 show the changes in *A* and *B* values as the fine material increases. As seen in the tables for all three range of airflows (0.006-0.022 m s^{-1}, 0.024-0.06 m $s^{-1}$and 0.067-0.178 m s^{-1}), *A* value decreases as the fine material increase and *B* value shows to be changing around 0.7 -1.0. Sokhansanj et al. (1993) has fitted these values for 6.4mm alfalfa pellets for the airflow range of 0.0053 - 0.82 m s^{-1} which falls within the first two ranges of airflow I tested.

Inspection for *A* and *B* values for wood pellets mixed with fines showed that while *A* values changed test to test, changes in *B* values was insignificant. By assigning a constant value for B, new values for A were obtained. New *A* values were plotted versus fine % to find the trend and relationship. Table 5.7 summarizes the obtained results. Figure 5.1 also shows a typical graph for changes in *A* value as fine content increases for the flow rate of 0.024-0.06 m s^{-1}.

Table 5.7. Relationship between A values and fine material (Constant B)

Airflow Range	Equation for A versus f	B	R^2
0.006-0.022 m s^{-1}	A = -0.0001f + 0.0029	0.93	0.92
0.024-0.06 m s^{-1}	A = -0.0001f + 0.0033	0.82	0.94
0.067-0.178 m s^{-1}	A = -0.0002f + 0.0046	0.77	0.89

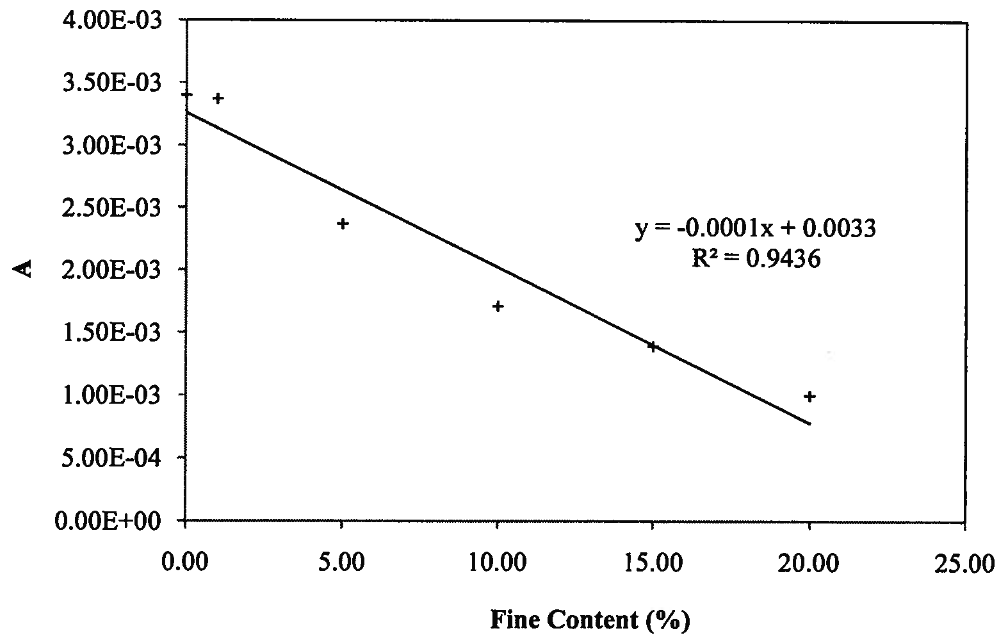

Figure 5.1 Constant A of Shedd equation as a function of fine content for the air flow range of 0.024-0.06 m s^{-1} (B=0.82).

5-2. Recommendations for future work

1- Buoyancy induced airflows due to differential temperature within a storage structure may be prevalent in wood pellet storage. The effect of surface roughness of pellets and single pellet porosity of pellets on these low airflow regimes need to be investigated.

2- All tests have done in this study have been in vertical direction. The same test can be done with the air flowing in the horizontal direction to compare the results in the resistance of wood pellets to airflow.

3- Expand research on that effects the ventilating air humidity have on the moisture content of pellets including

5-3. References

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APPENDIX A: EXPERIMENTAL AND PREDICTED DATA

Table A.1. Measured and predicted pressure drops relevant to Figure 2.3

Airflow ($m^3 s^{-1} m^{-2}$)	Experimental Pressure Drop ($Pa\ m^{-1}$)	Predicted by Hukill and Ive Equation ($Pa\ m^{-1}$)	Predicted by Ergun Equation ($Pa\ m^{-1}$)	Predicted by Shedd Equation ($Pa\ m^{-1}$)
0.0142972	8.7178	2.236723	5.505496	1.549944
0.0214458	12.454	4.268792	8.772478	3.247076
0.0285944	16.1902	6.828406	12.38228	5.487453
0.035743	18.681	9.886311	16.33491	8.243791
0.0428916	21.1718	13.42172	20.63036	11.49601
0.0500402	26.1534	17.41873	25.26863	15.22835
0.0571888	31.135	21.86462	30.24972	19.42789
0.0643374	36.1166	26.74885	35.57364	24.08373
0.071486	42.3436	32.06249	41.24038	29.18648
0.0786346	49.816	37.7978	47.24994	34.72791
0.0857832	54.7976	43.94802	53.60233	40.70071
0.0929318	62.27	50.50713	60.29753	47.09831
0.1000804	68.497	57.46971	67.33556	53.91476
0.107229	79.7056	64.83089	74.71641	61.14461
0.142972	115.8222	107.4717	116.763	103.3324
0.178715	174.356	159.5345	167.3802	155.2361
0.214458	241.6076	220.6975	226.5679	216.4776
0.250201	296.4052	290.7133	294.3262	286.76
0.285944	387.3194	369.3826	370.655	365.8401
0.321687	488.1968	456.5394	455.5544	453.5126
0.35743	570.3932	552.0426	549.0244	549.6009
0.393173	635.154	655.7696	651.0649	653.9498
0.428916	764.6756	767.6122	761.676	766.4216
0.464659	868.0438	887.4742	880.8576	886.8926
0.500402	981.3752	1015.269	1008.61	1015.251
0.536145	1127.087	1150.918	1144.933	1151.394
0.571888	1281.517	1294.349	1289.826	1295.227
0.607631	1399.83	1445.496	1443.29	1446.665
0.643374	1556.75	1604.297	1605.324	1605.625
0.679117	1820.775	1770.697	1775.929	1772.033
0.71486	2006.339	1944.642	1955.105	1945.818

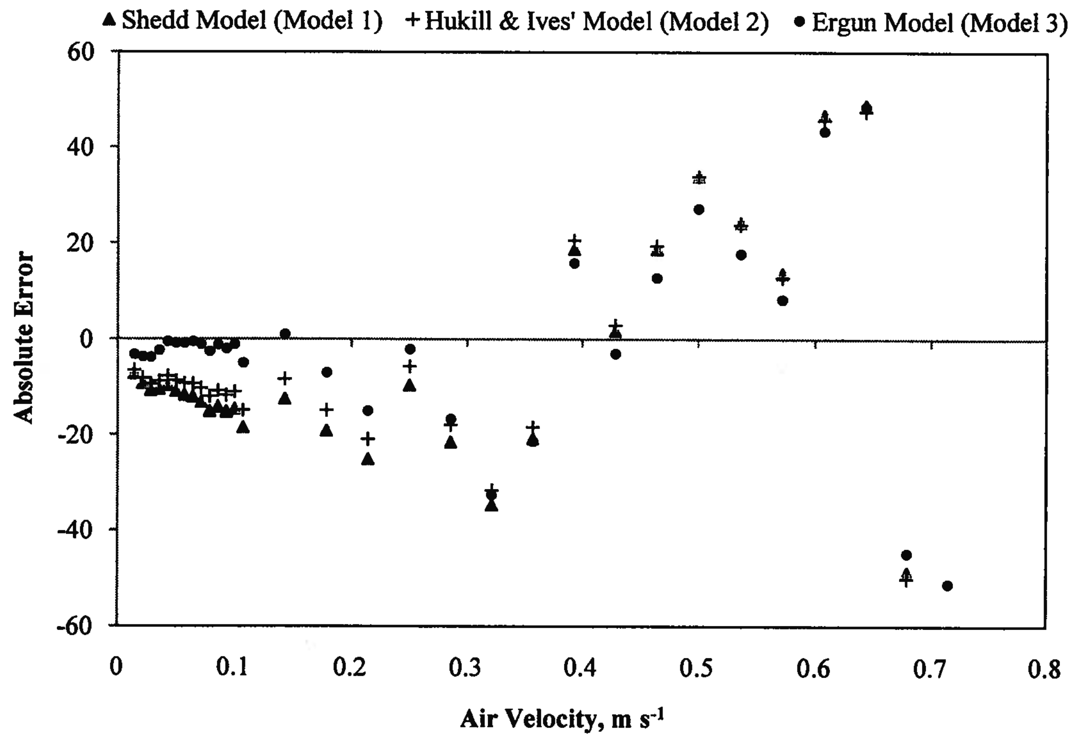

Figure A.1 Absolute error using three models (Relevant to data in page 76)

Table A.2. Measured and predicted pressure drops relevant to Figure 3.5

Airflow ($m^3 s^{-1} m^{-2}$)	Experimental Pressure Drop ($Pa\ m^{-1}$)	Predicted by Hukill and Ive Equation ($Pa\ m^{-1}$)	Predicted by Ergun Equation ($Pa\ m^{-1}$)	Predicted by Shedd Equation ($Pa\ m^{-1}$)
0.0002374	0.188679	0.03165	0.084108	0.001337
0.0003057	0.283019	0.040886	0.108352	0.002076
0.0003784	0.377358	0.050784	0.134191	0.003011
0.0004491	0.471698	0.060471	0.159338	0.004057
0.0005168	0.471698	0.069801	0.183431	0.005181
0.0005809	0.566038	0.078698	0.206287	0.006352
0.0023112	0.943396	0.337689	0.830966	0.070419
0.0028881	1.132075	0.4319	1.042621	0.103817
0.0042539	1.698113	0.669976	1.550513	0.203815
0.0048446	1.792453	0.779325	1.773144	0.255634
0.0062407	2.358491	1.052558	2.306358	0.397374
0.0074676	2.641509	1.309417	2.783186	0.54324
0.0078816	2.830189	1.399542	2.945826	0.596783
0.0089369	3.207547	1.636971	3.364318	0.742816
0.0104541	3.962264	1.997399	3.97599	0.976156
0.0127035	4.622642	2.571919	4.904447	1.370752
0.0138648	5.09434	2.886812	5.393897	1.596392
0.0157658	5.943396	3.428459	6.20997	1.99687
0.0164929	6.132075	3.644071	6.526972	2.160029
0.0187145	6.981132	4.331273	7.512316	2.691944
0.0194668	7.358491	4.573542	7.851702	2.883264
0.020729	7.924528	4.990732	8.427634	3.216748
0.0220065	8.301887	5.426425	9.018761	3.569933
0.0142972	7.169811	3.007181	5.5779	1.684124
0.0214458	9.811321	5.233539	8.75829	3.412992
0.0285944	11.98113	7.882979	12.19964	5.633597
0.035743	15.37736	10.93035	15.90195	8.310147
0.0428916	18.67925	14.35712	19.86522	11.41687
0.0500402	22.45283	18.14887	24.08945	14.93387
0.0571888	26.22642	22.2939	28.57464	18.84506
0.0643374	31.79245	26.7825	33.32079	23.13707
0.071486	36.60377	31.60637	38.3279	27.79845
0.0786346	42.35849	36.75834	43.59597	32.81928
0.0857832	46.98113	42.23211	49.125	38.19081
0.0929318	53.86792	48.02208	54.91498	43.90526
0.1000804	58.96226	54.12323	60.96593	49.95559

Airflow ($m^3 s^{-1} m^{-2}$)	Experimental Pressure Drop ($Pa m^{-1}$)	Predicted by Hukill and Ive Equation ($Pa m^{-1}$)	Predicted by Ergun Equation ($Pa m^{-1}$)	Predicted by Shedd Equation ($Pa m^{-1}$)
0.1072305	65.37736	60.5324	67.27919	56.33683
0.142974	92.16981	97.03817	102.754	92.99144
0.1787175	133.4906	140.7073	144.7529	137.1721
0.214461	188.3962	191.2435	193.276	188.4535
0.2502045	243.3962	248.4201	248.3233	246.5071
0.285948	315.0943	312.0558	309.8948	311.0676
0.3216915	366.9811	382.0003	377.9904	381.9139
0.357435	480.1887	458.1261	452.6103	458.8574
0.3931785	546.2264	540.3231	533.7543	541.7341
0.428922	626.4151	628.4946	621.4225	630.3998
0.4646655	730.1887	722.5548	715.6148	724.7257
0.500409	795.283	822.4265	816.3314	824.5961
0.5361525	929.2453	928.04	923.5721	929.9058
0.571896	1032.075	1039.332	1037.337	1040.559
0.6076395	1155.66	1156.244	1157.626	1156.467
0.643383	1266.981	1278.721	1284.439	1277.548
0.6791265	1430.189	1406.716	1417.777	1403.727

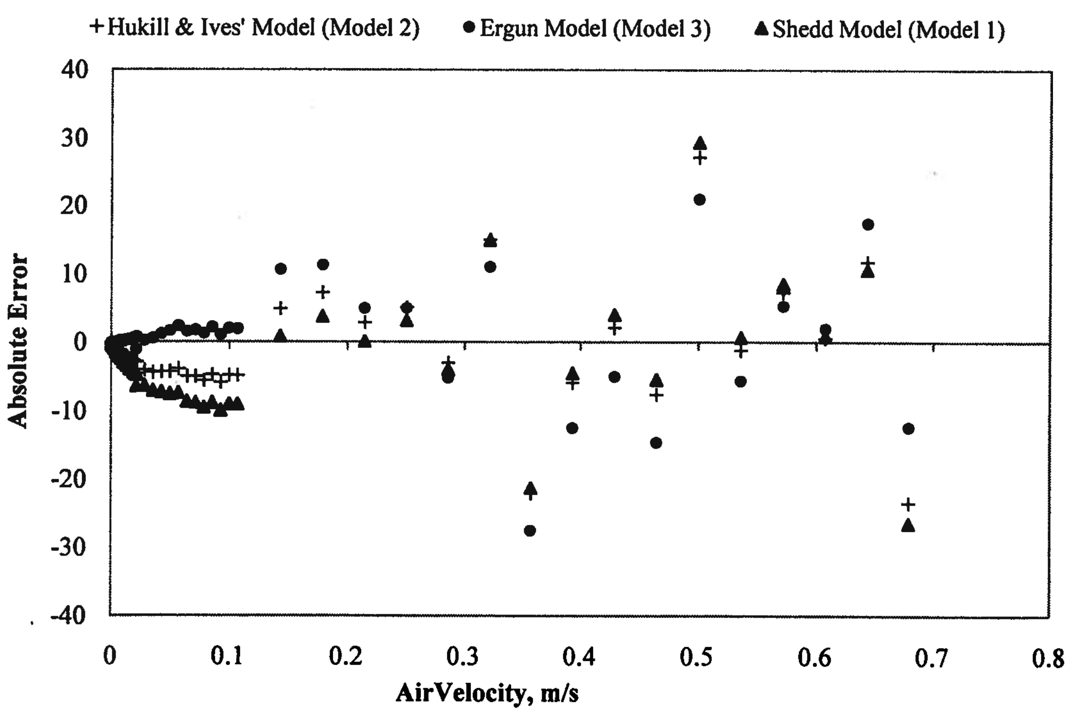

Figure A.2 Absolute error using three models (Relevant to data in page 78-79)

Appendix B: EXPERIMENTAL SET UP

Figure B.1 Photo of experimental equipment