Air flow versus pressure drop for bulk wood pellets

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ABSTRACT

Data on the resistance of wood pellets to air flow are required for the design and control of ventilation, cooling, 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 0.8 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 means and standard errors of the constants associated with these equations were then presented. The Ergun equation was found to provide the best fit to the data.

Keywords: Pressure drop; Air flow; Wood pellets; Ventilation; Ergun; Shedd; Hukill-Ives

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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 [1]. 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^{o}C and finally thermal cracking takes place at temperatures higher than 200^{o}C [3]. Preventive measures 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

[4]. 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 [5].

Sokhansanj et al. [6] fitted Shedd's equation [7] to experimental data for alfalfa pellets and cubes,

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

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 [8] 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 [9] suggested the following equation that relates air flow to pressure drop for agricultural materials:

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

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 [8]. The specified airflow range for alfalfa pellets is 0.0053 to 0.63 m s^{-1}.

Ray et al. [10] 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 x 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. [10] presented Shedd's constants $a_1$and b_1 for the tested pellets and cubes.

Kristensen and Kofman [11] 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; some 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 4 lists the transformed values for *a* and *b* as derived from their study.

Kristensen et al. [12] 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. did not have data on ranges in pellet lengths, bulk density, or moisture content of the pellets.

Hunter et al. [13] made a comparison between the Hukill-Ives model (Eq. 2) and Ergun's model [14] and suggested the following modified form of Ergun's equation,

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

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 et al. [13] reported values for R and S for 28 different grains.

Gayathri and Jayas [15] 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):

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

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. [16] 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 [17], and used a technique developed by Brooker [18] 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.

2. **Materials and methods**

2.1. Experimental apparatus

Fig. 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^{o}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}), we measured the pressure drop at 14 levels of airflow rates and for high airflow range (0.1072 m s^{-1} to 0.7148 m s^{-1}) we measured the pressure drop at 18 levels of flow rates. The ambient temperature and pressure were recorded during each test.

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 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. We shortened the length of sieving time to minimize the pellet breakage. We considered pellets with $L < 4$ mm 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 [19]:

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

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

The volume of an individual pellet was determined using a multi-pycnometer (Quantachrome Model MVP-D160-E). The unit uses nitrogen as displacement gas with a pressure of about 140 kPa (20 psig). Particle density was calculated by dividing the mass of the single particle by its volume. Triplicate measurements were made in all cases.

The bulk density of wood pellets was determined according to a modified ASAE Standard S269.4 DEC 01 [8]. 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 [20]. The tester uses 100g 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.

3. Results and discussion

Table 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}.

Fig. 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 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 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. We compared Shedd's constants for 6.4 mm alfalfa pellets estimated by Sokhansanj et al. [6] and those estimated by Ray et al. [10] for 6.7 mm feed pellets. The calculated pressure drops from Ray et al.'s data [10] were significantly higher those calculated from Sokhansanj et al.'s data [6]. 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. [10] recorded a bulk density of 710 kg m^{-3} for 6.4 mm pellets whereas Sokhansanj et al. [6] recoded a bulk density of 588 kg m^{-3} for similar size pellets. The analyzed data from this study was also shown in Table 4. The fitted parameters are much closer to the results derived from 28 mm cut willow chips [11, 12] than those of 6.4 mm alfalfa pellets and 6.7mm feed pellets [6, 10].

To observe how our selected equations predict the entire range of air flow rates, we calculated the percentage error of predicted versus experimental pressure drops, as a function of air flow rate, for mixed sizes of pellets. Fig. 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.

Fig. 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 ($L>6.7$mm) 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.

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.

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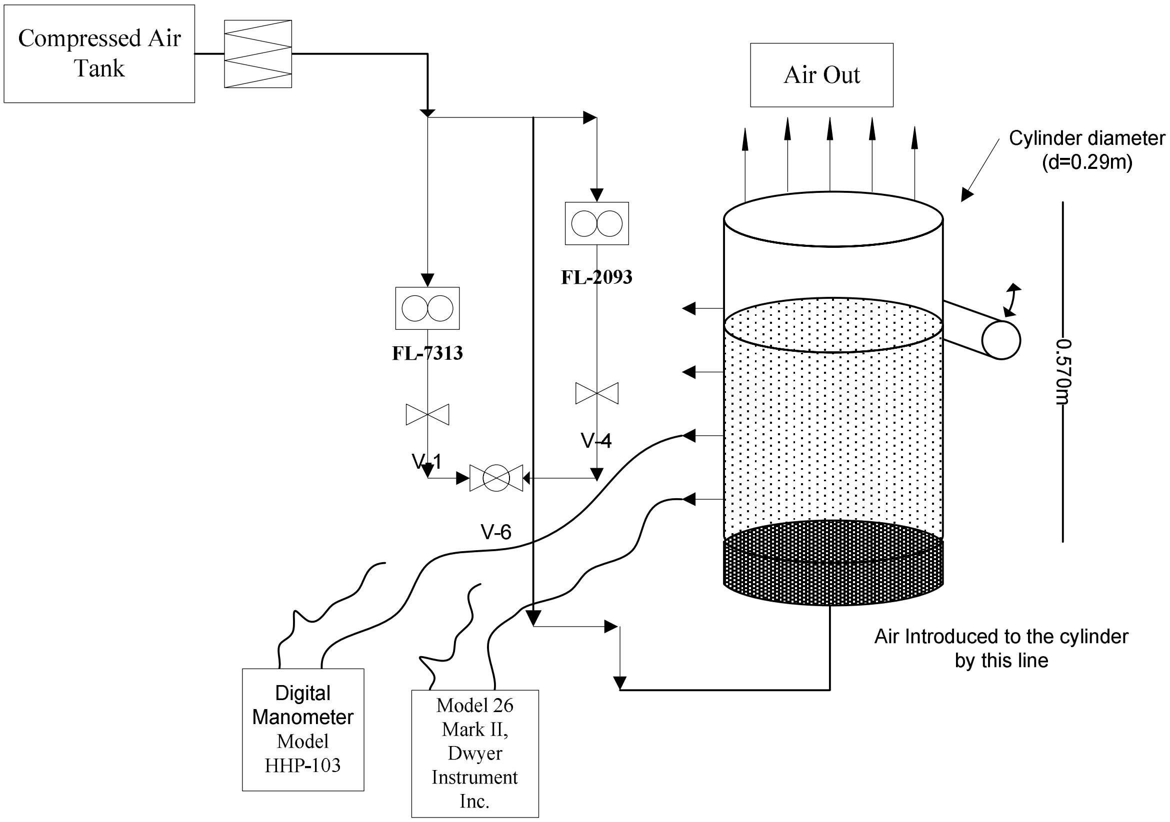
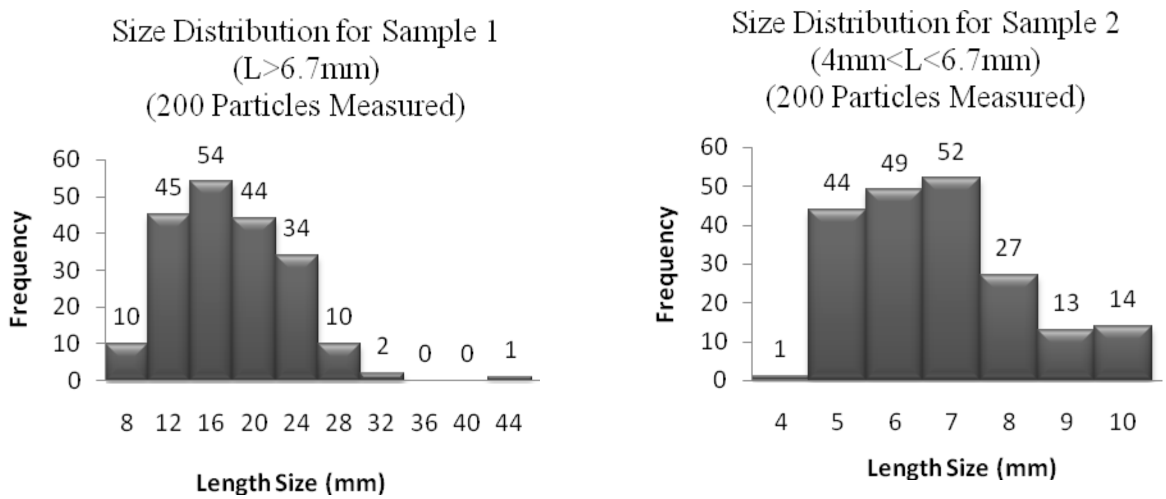


Fig. 1 - Equipment for measuring the resistance of wood pellets to air flows.



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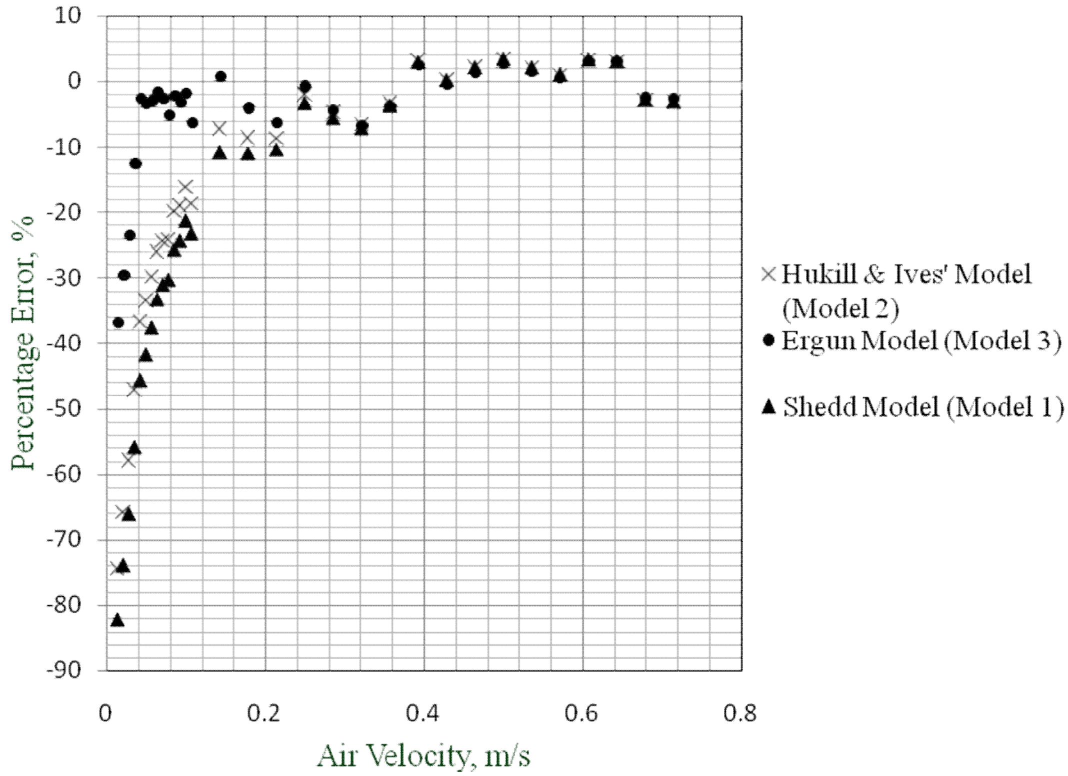

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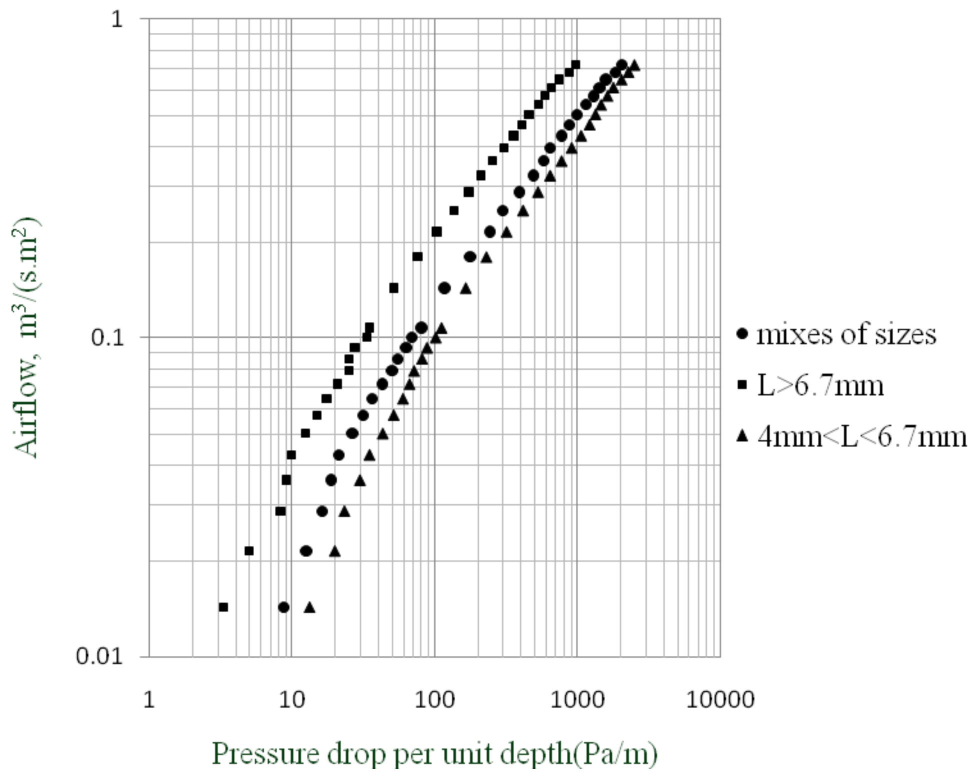

Fig. 4- Resistance of white wood pellets with different sizes to air flow

Table 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 – 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 3 - Estimated constants for the various predictive models

Equation 1 (Shedd's Equation)

Particle Size	Sample	a_1	b_1	Standard Error a_1	Standard Error b_1	S_y
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- Ive's Equation)

Particle Size	Sample	a_2	b_2	Standard Error a_2	Standard Error b_2	S_y
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 a_3	Standard Error b3	S_y
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 4 - Constants a_1 and b_1 in Shedd's equation among various materials

Product	Constant a_1	Constant 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