Airflow Resistance of Sugarbeet

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ABSTRACT

In Alberta, Canada, sugarbeet (*Beta vulgaris* L.) is stored in large outdoor piles prior to processing. Hot spots and mold damage may occur, especially if the piles are not ventilated. Airflow resistance data are required to predict the uniformity of airflow and design an optimum ventilation system. An airflow resistance device was designed and fabricated to measure the airflow resistance of sugarbeet. The sugarbeet roots were grouped into three size ranges: those weighing less than 1200 g, those weighing more than 1200 g, and mixed roots. Both clean roots and roots mixed with foreign material at a rate of 4.4 to 8.5% w/w were tested. Airflow rates of 0.01, 0.02, 0.04, 0.06, 0.08, 0.1, 0.3, and 0.5 $m^3/s/m^2$ were used. Airflow measurements were conducted with the bin in vertical and horizontal positions. Bulk density and porosity of sugarbeet roots affected airflow resistance. Two airflow resistance models, namely, Shedd's and Hukill and Ives' were fitted to the data. Small roots had airflow resistance up to 1.9 times that of large roots. Foreign materials in the roots caused increased airflow resistance.

Additional key words: airflow resistance device, pressure drop, ventilation

Sugarbeet is a major crop in southern Alberta, Canada. In 1999 and 2000, 839,773 and 920,252 tonnes were harvested, respectively (Alberta Sugar Beet Growers, 1999; 2000). Due to a short harvest window and limited processing capacity, harvested roots must be stored prior to processing. Piling typically begins in late September and usually continues into October. Processing begins immediately and usually continues into February or March, or until all roots are processed. Roots must be stored up to 120 days or more depending on the processing capacity and harvest volume.

Losses during storage are dependent on many factors including length of storage time, root temperature, ambient temperature, and the degree of mechanical and freezing injury (Wyse, 1978; Akeson et al., 1974; Wyse and Peterson, 1979; Cole, 1977). Peterson et al. (1987) estimated that roots lose from 0.15 to 0.25 kg of sugar per tonne per day during storage. Forced-air ventilation of piles has been effective in controlling high temperature buildup brought about by respiration of the roots in the pile, thereby reducing temperature and consequently reducing storage losses. Quamme (1952) showed that sugar losses were reduced by 50% when roots were ventilated at a rate of approximately 0.005 m^3/s/t (10 ft^3/min/ton). However, acceptance and installation of forced-air ventilation storage systems in Alberta has been limited. The costs associated with installing and operating a ventilation system must be offset by a decrease in storage losses.

Pockets of poor airflow distribution are a common problem in ventilated storage. Areas with poor airflow distribution tend to heat (hot spots) and eventually spoil. Holdredge and Wyse (1982) confirmed that hot spots tend to develop at locations where airflow is restricted. They concluded that soil and foreign matter on the roots in storage is an important factor in the occurrence of hot spots.

Uniformity of airflow distribution in a pile may be influenced by the size and shape of the roots, variation in directional resistances determined by the product shape and piling method, and the amount of soil mixed with the roots. Irvine et al. (1993) studied the effect of the above mentioned factors on the airflow resistance of potato tubers. Large tubers had 41% of the airflow resistance of small tubers. Loose soil increased the airflow resistance in the vertical direction.

Neale and Messer (1976) determined the airflow resistance of onion, carrot, and potato and concluded that the soil adhering to the crop had more effect on airflow resistance than variations in the physical properties of the crop itself. However, Small and Hodgkinson (1989) observed that soil contents in potato tubers of up to 5% had no effect on the static pressure variation in round duct ventilation systems but did have a small effect in half-round duct ventilation systems.

As a means to better define ventilation requirements, this study examined the pressure drop and airflow characteristics of ventilated sugarbeet roots. Airflow resistance is required to predict the airflow distribution within the ventilated pile of roots and to determine fan power requirements for adequate ventilation.

The objective of this study was to determine the airflow resistance of sugarbeet roots. The effect of root size, soil and foreign material present in the pile, and the airflow direction on the airflow resistance of roots was also investigated.

MATERIALS AND METHODS

Sample Selection

Sugarbeet samples were selected from freshly piled roots obtained from the storage piles at the Rogers Sugar Ltd. factory in Taber, Alberta in October 1998. The roots in these piles were produced in irrigated areas near Taber. The mean weight was about 1200 g/root. For the experiments, roots were sorted according to size as: a) those weighing less than 1200 g (small roots); b) those weighing more than 1200 g (large roots); and, c) mixed or unsorted roots (mixed roots). Excess soil was removed from selected roots. Selected roots were placed in: a) four wire pallet bins of large roots; b) four bins of small roots; and c) three bins of mixed roots. Each bin contained about 900 kg of roots. A wooden bin was filled with foreign matter (soil, stones, and plant parts) obtained from the piler. The materials were transported to the Agricultural Value-added Engineering Centre (AVEC) in Edmonton, AB for storage and testing. Prior to testing, the roots were stored indoors at temperatures below 9°C.

Airflow Resistance Device

Figure 1 shows the device used to measure the airflow resistance (pressure drop) of sugarbeet roots. The device consisted of a fan, duct, and bin to contain the roots. The bin was constructed with 51 mm x 51 mm x 5 mm angle bar and lined with 19 mm thick plywood and reinforced with 38 mm x 38 mm x 5 mm angle bar. The roots were separated from the plenum by a 6.4 mm (0.25 in.) diameter wire screen with openings of 19 mm square. Connecting the plenum of the bin and the 406 mm (16 in.) diameter duct, was a transition whose shape went from rectangle to round with an included angle was 60°. One wall of the bin was fabricated such that it could be removed for emptying and filling. The removable wall was divided into four sections; each section could be put in place or

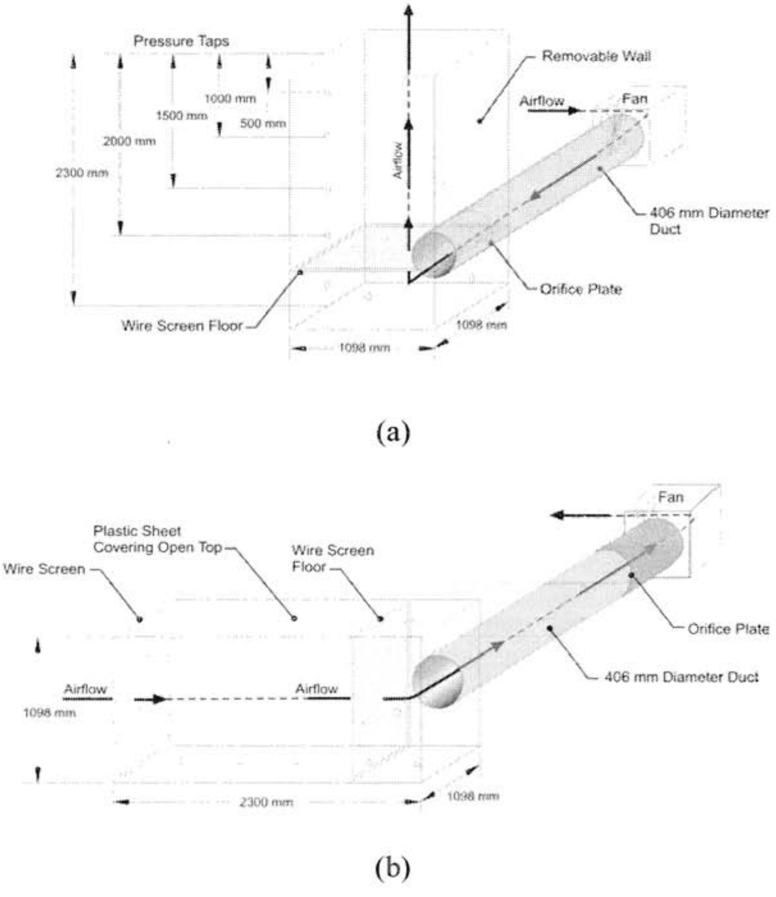

Figure 1. Device used to measure airflow resistance of sugarbeet. (a) Vertical airflow direction. (b) Horizontal airflow direction.

removed to facilitate loading and unloading. The device was painted inside and out. A sealing system was incorporated to prevent air leakage around each section. The four walls of the container were lined with 25.4 mm (1 in.) thick closed-cell polyethylene foam. A silicone sealant was also applied around the inner perimeter lining. The inside dimensions of the bin holding the roots were 1 m wide x 1 m long x 2 m high. During testing in the vertical airflow direction (Figure 1(a)), the top of the bin was left open. The air was introduced into the bottom of the bin.

The bin was also designed and fabricated so that it could be oriented horizontally (Figure 1 (b)) to measure airflow resistance with a horizontal airflow. The removable wall became the top for this setup. During tests, this wall was removed and a polyethylene sheet was placed on top of the roots. To contain the roots, a removable wire screen wall was installed at the end, opposite the fixed screen. In this configuration, the fan was installed to draw air through the roots under negative pressure. The negative pressure caused the polyethylene sheet to seal and prevent airflow through what would have been "head space" over the roots.

Airflow Control and Measurement

Airflow was supplied by a Lau Model No. BLFGP15-9A centrifugal fan (Phillips-Lau, Kitchener, ON) driven by a 4 kW (3 hp) Baldor SmartMotor™(Baldor Electric Co., Ft. Smith, AR) which is an integrated industrial motor and inverter control. The duct diameter was 406.4 mm (16 in.). Airflow rate was measured by square-edged orifice plates (Jorgensen, 1983). Two orifice plates were constructed of 3.2 mm (0.125 in.) thick flat black steel with diameter ratios of 0.35 and 0.60 to measure airflow rates from 0.01 to 0.10 $m^3/s/m^2$ and 0.20 to 0.50 $m^3/s/m^2$, respectively. Flange taps were inserted at 25.4 mm (1 in.) from either side of the orifice plate to measure differential pressure. The orifice plate was located 10 duct diameters (4.1 m) away from the fan in the vertical and horizontal airflow tests to ensure straight airflow. Differential pressures across the plates and static pressures upstream of the plates greater than 124.4 Pa (>0.5 in. H_2O) were measured using a Dwyer Model 125 AV inclined manometer (Dwyer Instruments Inc., Michigan City, IN) (250 Pa = 1 in. H_2O). For pressures less than 124.4 Pa (<0.5 in. H_2O), a pressure transducer (Model PX 653-0.5D5V, Omega Engineering, Inc., Stamford, CT) with an accuracy of 0.25% full scale (124.4 Pa full scale) was used. The cross sectional area of the bin was 1 m^2.

Airflow Resistance Measurement

Static pressures at 0.5, 1.0, 1.5, and 2.0 m from the top of the bin were measured for airflow rates of 0.01, 0.02, 0.04, 0.06, 0.08, 0.10, 0.20, 0.30, 0.40, and 0.50 $m^3/s/m^2$ (1 $m^3/s/m^2$ = 196.85 $ft^3/min/ft^2$). Since the pressure drop per unit meter depth measurements were low at the low airflow rates, e.g. 0.01 $m^3/s/m^2$, the bin was constructed to 2 m in depth to allow for more accurate measurement.

Static and differential pressures less than 124.4 Pa were measured using the differential pressure transmitter (Model PX 653-0.5D5V, Omega Engineering. Inc., Stamford, CT). Pressures between 124.4 and 248.8 Pa were measured using the Dwyer Model 125 AV inclined manometer (Dwyer Instruments Inc., Michigan City, IN) with a 248.8 Pa (1.0 in. H_2O) full scale and minor divisions of 1.2 Pa (0.005 in.

H_2O). Pressures above 248.8 Pa were measured using the Dwyer Model 400-23 inclined-vertical manometer (Dwyer Instruments Inc., Michigan City, IN). The inclined portion of this manometer can measure to 547.4 Pa (2.2 in. water) with minor divisions of 5 Pa (0.02 in.) (1 in. water = 248.84 Pa).

In the vertical airflow tests, the system was under positive pressure. Clean roots were loaded manually through the open side of the bin via the four-section removable wall. Sections of the wall were installed as the depth of the roots increased. Each section of the wall was lined with foam to prevent air leakage. During unloading, the section of the removable wall nearest the top was removed first.

For the horizontal airflow tests, the system was under negative pressure. The duct was relocated such that the orifice plates were 10 duct diameters from the bin. The removable wall portion of the bin became the top and a removable wire screen was installed in the end (top in the vertical position) of the bin to contain the roots (Figure 1 (b)).

For the experimental trials that required the addition of foreign matter, these materials were added gradually and spread evenly while the roots were loaded. After airflow resistance measurements were completed, the foreign materials were retrieved and stored separately in a wooden bin.

Experimental Design

In this experiment, the factors were: a) root size; b) foreign matter content; and c) airflow direction. Airflow resistance was measured in duplicate. Root sizes were: a) small; b) large; and, c) mixed roots. Foreign matter content was based on a typical value provided by Rogers Sugar, which is between 4 and 5% by weight. The two levels of foreign matter content were: a) 0% or clean roots; b) 4 to 5% for the small and large roots, and 8.5% for the mixed roots. The experiments lasted for about one month and by the time the airflow resistance of mixed roots with foreign matter was measured, the root pieces and plant materials in the bin containing the foreign matter were deteriorating. Thus, the foreign matter occupied less volume. The roots also lost weight due to dehydration, which explains the high foreign matter content of the mixed roots. Airflow direction consisted of: a) vertical; and b) horizontal airflows.

Measurement of Moisture and Density

Moisture content of the roots used for airflow resistance measurement was determined by the oven method. Five samples each of mixed, small, and large roots were randomly chosen for moisture determination. Each root was ground in a food blender and a 15 g sample of ground root was used. For each root, three replicated samples were dried in a mechanical convection oven at 75°C for 48 hours and the moisture was reported in percent wet basis. Each root size had 15 measurements (five samples x three replicates).

Bulk density was determined each time the bin was filled, by weighing all roots prior to filling the 2 m^3 volume bin. In tests where foreign matter was added, the foreign matter weight was also included in the calculation of bulk density. Root particle density was determined by slicing root samples to fit the 135 cm^3 cup of the Micromeritics multivolume pycnometer 1305 (Micromeritics Instrument Corp., Norcross, GA). Using Helium gas, the pycnometer determined the skeletal volume of the sample. Particle density was the ratio of mass to the skeletal volume of the sample expressed in kg/m^3. The porosity (%) or percent volume occupied by air in the measuring bin during each test was calculated from the particle density and bulk density values.

Airflow Resistance Analysis

Two models were used to fit the data. The first model by Shedd (1953) is represented by the following:

$$Q = A\left(\frac{\Delta P}{L}\right)^{B} \qquad (1)$$

where:

Q = airflow rate per unit area, $m^3/s/m^2$

$\frac{\Delta P}{L}$ = pressure drop per unit depth, Pa/m

A, B = experimental constants for each test condition

This equation can be easily manipulated to perform reverse calculation as:

$$\frac{\Delta P}{L} = A'(Q)^{B'} \qquad (2)$$

where:

A', B' = experimental constants for each test condition.

The second model by Hukill and Ives (1955) is described in ASAE D272.2 DEC 95 (ASAE, 1996). This model calculates pressure drop per unit depth from a known airflow rate per unit area:

$$\frac{\Delta P}{L} = \frac{AQ^2}{\ln(1+BQ)} \tag{3}$$

where:

A, B = experimental constants for each test condition

The nonlinear regression procedure, PROC NLIN of SAS (SAS, 1987) was used to fit the models to the data and determine A' and B' of equation 2, and A and B of equation 3.

RESULTS AND DISCUSSIONS

Pressure Drop Measured at Different Points in the Bin

In the vertical airflow tests (Figure 2(a)), the pressure drop per unit depth at the bottom of the bin ($Pv_{2.0}$) was usually the highest, followed by the pressure drop 0.5 m above the floor ($Pv_{1.5}$). The pressure drop nearest to the top of the bin ($Pv_{0.5}$) was usually the lowest. Irvine et al. (1993) reported a similar trend for potato. They obtained pressure values from the central 0.7 m portion of a 1.0 m deep bin. The variability of pressure at a given airflow rate may be due to the compression of the roots in the lower portion of the bin in the vertical airflow tests. For the vertical airflow tests, the $Pv_{1.5}$ and $Pv_{1.0}$ measurements were used in subsequent analysis.

In the horizontal airflow tests (Figure 2(b)), the pressure drop, $Ph_{2.0}$, $Ph_{1.5}$, and $Ph_{1.0}$, measured at 2.0, 1.5, and 1.0 m, from the removable wire screen, were similar for mixed and small roots. However, for large roots, $Ph_{1.5}$ was usually higher than the $Ph_{2.0}$ measurements. $Ph_{2.0}$ and $Ph_{1.0}$ were similar. Only $Ph_{0.5}$, measured 0.5 m from the removable wire screen, was lower in all tests. The effect of compression of roots was not obvious in the horizontal tests. The $Ph_{1.5}$ and $Ph_{1.0}$ values were used in subsequent analyses.

Table 1 shows the average pressure drop values of $Pv_{1.5}$ and $Pv_{1.0}$, and $Ph_{1.5}$ and $Ph_{1.0}$ at airflow rates of 0.55, 0.11, and 0.06 $m^3/s/m^2$. The coefficient of variation (CV) (the ratio of standard deviation and mean) of pressure drop values, from four replicates, ranged from 0.48% to 18.43% at airflow rate of 0.55 $m^3/s/m^2$. The CV was between 1.63% and 27.92% at an airflow rate of 0.11 $m^3/s/m^2$ and between 3.92% and 46.05% at an airflow rate of 0.06 $m^3/s/m^2$. The CV increased at lower airflow rates, indicating more variability in airflow resistance measurements. However, the CV values were similar to those reported by Irvine et al. (1993) for potato.

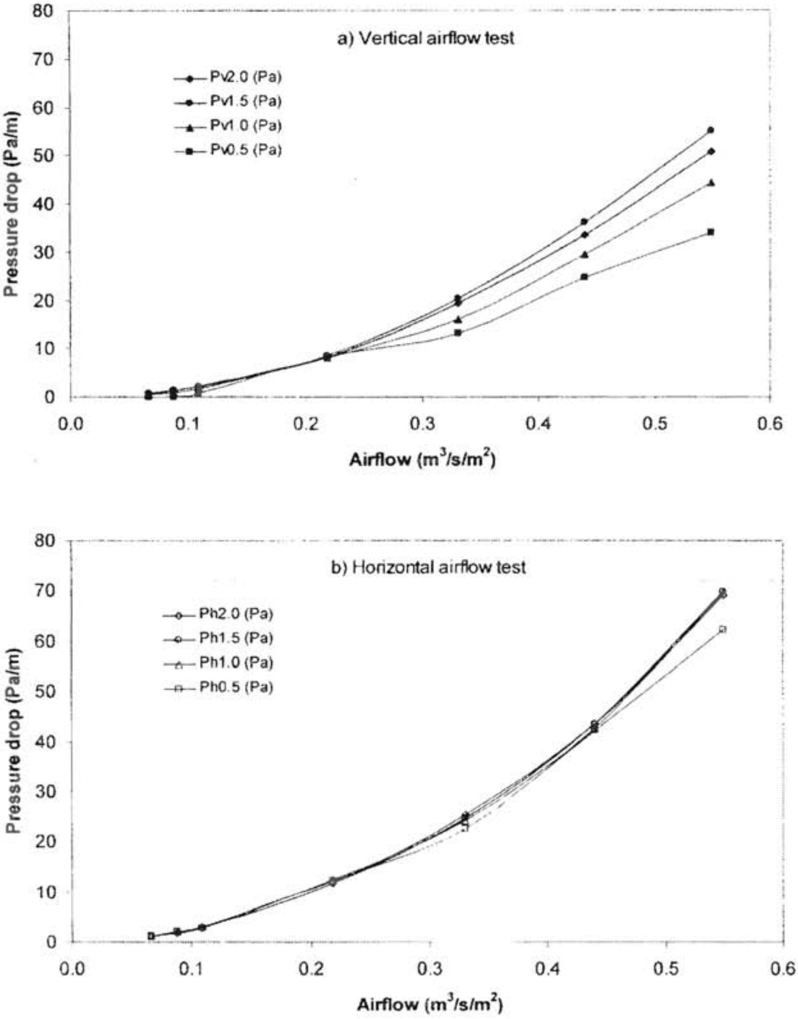

Figure 2. Pressure drop per unit depth at different pressure tap locations for mixed roots with 0% foreign matter.

Fitting Models to Pressure Drop Data

The models represented by equations 2 and 3 were fitted to the pressure drop data using nonlinear regression analysis, PROC NLIN (SAS, 1987). The estimates of constants A', B' , A, and B, as well as the coefficient of determination (R^2) and sum of squares of the residuals (SS) for different samples and test conditions are listed in Table 2. The R^2 value ranged from 0.96 to 0.99 indicating that both models fit the

Table 1. Average pressure drop ($\Delta P/L$) at airflow rates of 0.55, 0.11, and 0.06 $m^3/s/m^2$.

Root size	Foreign matter	$\Delta P/L$ @ $Q = 0.55\ m^3/s/m^2$		$\Delta P/L$ @ $Q = 0.11\ m^3/s/m^2$		$\Delta P/L$ @ $Q = 0.06\ m^3/s/m^2$	
		Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
	%	Pa/m					
Mixed	0	49.723	69.766	1.952	2.908	0.519	1.184
		(6.437)[†]	(0.335)	(0.545)	(0.498)	(0.239)	(0.142)
		(12.95%)[‡]	(0.48%)	(27.92%)	(17.13%)	(46.05%)	(11.99%)
	8.53	129.583	138.535	6.717	7.294	3.523	3.037
		(10.025)	(15.006)	(0.306)	(0.596)	(0.810)	(0.226)
		(7.74%)	(10.83%)	(4.56%)	(8.17%)	(22.99%)	(7.44%)

[†] Standard deviation

[‡] Coefficient of variation

$n = 4$

(continued)

Table 1 (continued). Average pressure drop ($\Delta P/L$) at airflow rates of 0.55, 0.11, and 0.06 $m^3/s/m^2$.

Root size	Foreign matter	$\Delta P/L$ @ $Q = 0.55\ m^3/s/m^2$		$\Delta P/L$ @ $Q = 0.11\ m^3/s/m^2$		$\Delta P/L$ @ $Q = 0.06\ m^3/s/m^2$	
		Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
	%			Pa/m			
< 1200 g	0	75.415	89.476	4.272	4.200	1.944	1.963
		(13.896)	(7.196)	(0.621)	(0.266)	(0.260)	(0.273)
		(18.43%)	(8.04%)	(14.54%)	(6.33%)	(13.37%)	(13.94%)
	4.39	189.628	119.426	10.661	4.011	5.024	1.645
		(31.221)	(15.885)	(1.931)	(0.521)	(0.766)	(0.179)
		(16.46%)	(13.30%)	(18.11%)	(12.99%)	(15.25%)	(10.88%)

† Standard deviation ‡ Coefficient of variation n = 4

(continued)

Table 1 (continued). Average pressure drop (ΔP/L) at airflow rates of 0.55, 0.11, and 0.06 $m^3/s/m^2$.

Root size	Foreign matter	ΔP/L @ Q = 0.55 $m^3/s/m^2$		ΔP/L @ Q = 0.11 $m^3/s/m^2$		ΔP/L @ Q = 0.06 $m^3/s/m^2$	
		Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
	%	Pa/m					
> 1200 g	0	39.712	60.523	2.467	3.136	1.302	1.404
		(5.759)	(4.629)	(0.146)	(0.105)	(0.051)	(0.080)
		(14.50%)	(7.65%)	(5.92%)	(3.35%)	(3.92%)	(5.70%)
	4.5	88.334	91.387	4.904	3.930	2.247	1.601
		(0.523)	(8.792)	(0.260)	(0.064)	(0.112)	(0.139)
		(0.59%)	(9.62%)	(5.30%)	(1.63%)	(4.98%)	(8.68%)

† Standard deviation ‡ Coefficient of variation n = 4

Table 2. Fitting Shedd's (Model 1) model to the experimental airflow resistance data.

Root size	Airflow	Foreign matter (% mass)	Model 1 $\frac{\Delta P}{L} = A'(Q)^{B'}$				
			A' estimate	B' estimate	R^2	Sum of squares residual	$\Delta P/L$ (Pa/m) @ $Q = 0.1\ m^3/s/m^2$
Mixed	Vertical	0	159.83	1.94	0.98	190.16	1.84
Mixed	Vertical	8.53	426.92	1.98	0.99	487.34	4.47
Mixed	Horizontal	0	234.01	2.03	0.99	20.46	2.18
Mixed	Horizontal	8.53	445.92	1.94	0.99	1131.60	5.12
<1200 g	Vertical	0	228.94	1.85	0.96	996.49	3.23
<1200 g	Vertical	4.44	603.28	1.91	0.97	4216.86	7.42
<1200 g	Horizontal	0	282.4	1.92	0.99	287.46	3.4
<1200 g	Horizontal	4.33	459.82	2.24	0.98	1344.38	2.65
>1200 g	Vertical	0	116.69	1.82	0.97	171.44	1.77
>1200 g	Vertical	4.57	275.3	1.9	0.99	25.74	3.47
>1200 g	Horizontal	0	193.09	1.96	0.99	121.80	2.12
>1200 g	Horizontal	4.43	296.91	1.95	0.99	290.34	3.33

(continued)

Table 2 (continued). Fitting Hukill and Ives' (Model 2) model to the experimental airflow resistance data.

Root size	Airflow	Foreign matter (% mass)	Model 2 $\frac{\Delta P}{L} = \frac{AQ^2}{\ln(1+BQ)}$				
			A estimate	B estimate	R^2	Sum of squares residual	$\Delta P/L$ (Pa/m) @ $Q = 0.1\ m^3/s/m^2$
Mixed	Vertical	0	3030.91	158699072	0.98	190.17	1.83
Mixed	Vertical	8.53	10285.47	$4.24\mathrm{x}10^{10}$	0.99	488.96	4.64
Mixed	Horizontal	0	11884.55	$5.05\mathrm{x}10^{22}$	0.99	23.85	2.38
Mixed	Horizontal	8.53	5950.78	734794	0.99	1129.94	5.31
<1200 g	Vertical	0	1692	1565.99	0.96	994.72	3.34
<1200 g	Vertical	4.44	7118.24	130704	0.97	4213.38	7.51
<1200 g	Horizontal	0	3672.39	441718	0.99	287.04	3.43
<1200 g	Horizontal	4.33	15477.73	$4.31\mathrm{x}10^{17}$	0.97	1533.49	4.04
>1200 g	Vertical	0	686.91	361.74	0.97	169.76	1.9
>1200 g	Vertical	4.57	2476	8899.93	0.99	25.22	3.64
>1200 g	Horizontal	0	4664.03	$3.20\mathrm{x}10^{10}$	0.99	121.70	2.13
>1200 g	Horizontal	4.43	5641.04	187389391	0.99	290.31	3.37

data very well. The SS values were similar for each model. However, model 2 (Hukill and Ives, 1955; ASAE, 1996) tended to estimate very high values for constant B. Figure 3 shows the fit of the models to the data; both models had similar plots.

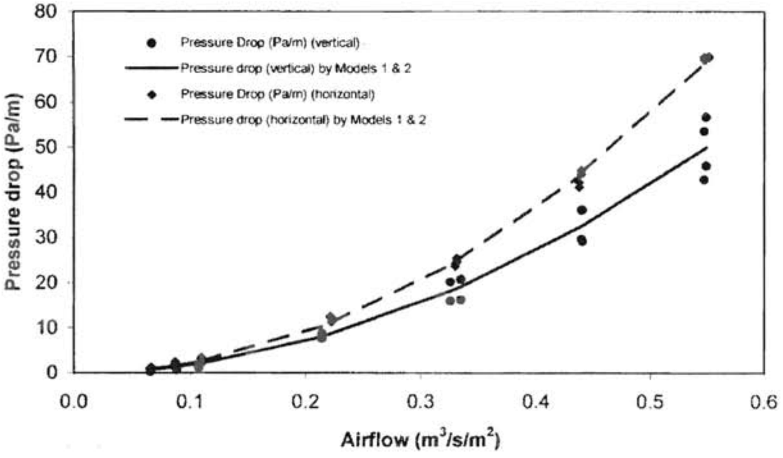

Figure 3. Fitting models 1 and 2 to airflow resistance data for clean mixed roots.

Physical Properties of Sugarbeet

Table 3 shows the physical properties of the roots used in the test. The size of roots was characterized by the mean mass as discussed earlier. Moisture contents were similar, ranging from 67.29% wet basis (wb) to 69.50%. The bulk density was dependent on whether the roots were clean or combined with foreign matter. Small roots generally had the highest bulk density (682.00 and 722.45 kg/m^3). Bulk densities of the large and mixed roots were similar with values ranging from 635.00 to 714.75 kg/m^3. The addition of foreign matter increased bulk density values. Root particle density values were also similar. Porosities were similar for clean roots in each size range, and similar but lower for roots with foreign matter.

Effect of Root Size

For clean roots (0% foreign matter), small roots had the highest airflow resistance (pressure drop), followed by mixed roots and the lowest was for large roots at an airflow rate of 0.55 $m^3/s/m^2$ (Table 1). Airflow resistance of small roots was 1.9 times that of the large roots. This was because small roots have higher bulk density than the other size ranges.

Table 3. Physical properties of sugarbeet roots.

Root size	Airflow	Foreign matter	Moisture content	Bulk density	Particle density	Porosity
		% mass	% wb	kg/m^3	kg/m^3	%
Mixed	Vertical	0	69.08 ± 1.53	635.00	1219.11	47.91
Mixed	Vertical	8.53	69.08 ± 1.53	714.75	1219.11	41.37
Mixed	Horizontal	0	69.08 ± 1.53	664.50	1219.11	45.49
Mixed	Horizontal	8.53	69.08 ± 1.53	714.75	1219.11	41.37
<1200 g	Vertical	0	67.29 ± 1.92	682.00	1240.21	45.01
<1200 g	Vertical	4.44	67.29 ± 1.92	722.45	1240.21	41.75
<1200 g	Horizontal	0	67.29 ± 1.92	687.50	1240.21	44.57
<1200 g	Horizontal	4.33	67.29 ± 1.92	699.25	1240.21	43.62
>1200 g	Vertical	0	69.50 ± 1.73	646.05	1249.19	48.28
>1200 g	Vertical	4.57	69.50 ± 1.73	691.90	1249.19	44.61
>1200 g	Horizontal	0	69.50 ± 1.73	665.00	1249.19	46.77
>1200 g	Horizontal	4.43	69.50 ± 1.73	683.13	1249.19	45.31

Small roots consistently had the highest airflow resistance at the lower airflow rates (0.11 and 0.06 $m^3/s/m^2$). At an airflow of 0.11 $m^3/s/m^2$, the airflow resistances of the mixed and large roots were not significantly different. However, at the 0.06 $m^3/s/m^2$ airflow rate, the large roots had higher airflow resistance than the mixed roots, which is inconsistent with the trend at the high airflow rates.

Effect of Airflow Direction

Airflow resistance of sugarbeet was measured in vertical and horizontal directions since it is known that agricultural products are not isotropic. The possibility that airflow resistance for grains may depend on airflow direction has been pointed out. Even canola (rapeseed) grains, which are spherical, have been reported to have lower airflow resistance in the horizontal airflow direction than vertical (Jayas et al. 1987). Since sugarbeet root is elongated, airflow resistances in both horizontal and vertical airflow direction were measured. These airflow resistance values are useful in mathematical modeling of pressure patterns in a sugarbeet pile.

Table 1 shows the effect of airflow direction, for the mixed, small, and large roots, at 0% foreign matter. The airflow resistance for all airflow rates was higher for the horizontal airflow direction than for the vertical direction. Irvine et al. (1993) reported 15 to 30% higher airflow resistances of potato in vertical over that of horizontal airflow direction. They attributed this difference to the orientation of potatoes during piling, where the tubers tend to orient themselves with respect to the horizontal. This was not the case for sugarbeet. Sugarbeet is shaped like a double cone (a short and a long cone connected together by their bases). For the airflow resistance tests, roots were manually loaded into the bin in a random manner without preference of orientation. At airflow rate of 0.55 $m^3/s/m^2$, the airflow resistance of roots (0% foreign matter) was up to 52% higher for the horizontal airflow direction than the vertical airflow direction. This can be explained by the bulk density and porosity values shown on Table 3. The tests for horizontal airflow direction for mixed, small, and large roots at 0% foreign matter, resulted in higher bulk densities and lower porosities than the tests for vertical airflow direction. As such, in the same volume of bin, more resistance was caused by roots in the horizontal airflow direction on account of their higher bulk density and lower porosity than the roots in vertical airflow direction.

For small roots (0% foreign matter), airflow resistance values were similar for both vertical and horizontal airflow at the lower airflow (0.11 and 0.06 $m^3/s/m^2$). At 0.55 $m^3/s/m^2$, horizontal airflow resistance was slightly higher (89.5 Pa/m) than for vertical airflow (75.4 Pa/m) however, these values were not significantly different. The bulk density of small roots with 0% foreign matter was slightly higher for the horizontal airflow direction tests (687.5 kg/m^3) than for the vertical direction tests (682.0 kg/m^3). It would have been ideal if the same bulk densities could have been attained in the bin for each test to examine the effect of airflow direction, but this was not possible. Thus, the difference in airflow resistance between horizontal and vertical airflow directions can be attributed to bulk density and porosity.

Effect of Foreign Matter

Foreign matter such as soil, stones, and plant parts increased airflow resistance. Airflow resistance values for roots with foreign matter were between 1.3 to 2.6 times that of the clean roots at an airflow of 0.55 $m^3/s/m^2$. At airflows of 0.11 $m^3/s/m^2$, airflow resistance for roots containing foreign matter were between 1.06 to 3.75 times the airflow resistance for clean roots. At airflows of 0.06 $m^3/s/m^2$, airflow resistance of roots combined with foreign matter was 1.1 to 6.8 times that of clean roots. The resistance to airflow was greater for small roots with foreign matter in the vertical direction than clean roots of the same size and airflow direction. Foreign matter obstructed airflow more so in the vertical than in the horizontal direction. Foreign matter also increases the bulk density and decreases the porosity of sugarbeet. Thus, the presence of foreign matter in a pile of sugarbeet had the most significant effect on airflow resistance. The presence of foreign material has to be taken into account when choosing fans for aerating or ventilating a sugarbeet pile for it will affect the fan static pressure and the uniformity of airflow.

Conclusions

1) Airflow rate is related to the pressure drop as described by the two models used in this study, namely, model 1 (Shedd's model) and model 2 (Hukill and Ives' model). These models fit the observed values well. These models and the estimated parameters can be used to estimate the static pressures required by fans in ventilating sugarbeet piles.
2) Bulk density and porosity of the piled sugarbeet roots affected airflow resistance. Higher bulk density and lower porosity resulted in higher airflow resistance, thus, higher static pressure is required of the ventilating fan.
3) Small roots had higher airflow resistance than the large and mixed roots. Bulk density values of small roots were higher than the large and mixed roots.
4) Due to different bulk densities for horizontal and vertical airflow direction tests, the effect of airflow direction cannot be properly evaluated.
5) The presence of foreign matter in the roots had the most important effect on airflow resistance. At low airflow rates, foreign matter increased the airflow resistance to as high as 6.8 times that of clean roots. At high airflow rates, airflow resistance was as high as 2.6 times that of clean roots.

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