Natural Resources Canada | Ressources naturelles Canada

CanmetMINING

Performance Evaluation of Schauenburg Industries Ltd. Fiberglass Ventilation Ducting

by S. Hardcastle, K. Butler and G. Li

Work performed for:
Schauenburg Industries Ltd.
North Bay, ON

Project: P-002288.001
Report: CMIN 2015-8607503-RE
Version: November 2015

PROTECTED B Business Confidential Information

For your convenience we are sending an electronic version of the report as the preliminary Deliverable for the contract. Please note however that since the electronic version may be altered during or after transmission, should any discrepancies arise between versions, CanmetMINING will support only the original electronic version of the report maintained at the Business Office of CanmetMINING.

Canada

EXECUTIVE SUMMARY

CanmetMINING were approached to evaluate the resistance to airflow of two styles of fiberglass ventilation ducting manufactured by Schauenburg Industries Ltd., North Bay, Ontario. Recently, the company had changed their manufacturing process of fiberglass ventilation ducting with a view to reducing the internal surface roughness and thereby its resistance to airflow. Consequently, the company was interested in determining if the new process improved the marketability of their product and were supported in this evaluation by the National Research Council of Canada's Business Innovation Access Program (BIAP) as administered through their Industrial Research Assistance Program (IRAP). Industry end-users were also interested in obtaining definitive expert derived resistance values under controlled circumstances to help them choose between the varieties of ventilation duct products available.

A test was specifically designed in consultation with Schauenburg Industries and Hurley Ventilation Technology (HVT), a fan manufacturer, to provide frictional pressure losses that could be confidently measured over a relatively short length of ducting. This test involved using a ~60 m (200 ft) length, comprised of 10 sections of ~0.6 m (2 ft) diameter duct attached to a fan of a suitable power with speed control at HVT's manufacturing facility. This arrangement allowed the measurement of frictional pressure loss over nine contiguous sections of each manufacture style of ducting at different fan speeds/air delivery rates. This surface condition could be considered as representative of an ideal installation.

The test was successful in generating consistent and repeatable results for both duct finishes, at two fan speed conditions, both for pressure loss along the whole length and for nine ~5.9 m (19.5 ft) sections of assembled ducting, and for airflow at up to five intermediary cross-sections. This testing indicated the assembled section of old style manufactured ducting to have a k factor resistance 0.00226 ± 0.00015 kg/m^3 (12.2 ± 0.8 $\times$ 10^{-10} lb•min^2/ft^4 imperial) while the new style manufacture had decreased the resistance by 22% to a k factor 0.00177 ± 0.00009 kg/m^3 (9.5 ± 0.5 $\times$ 10^{-10} lb•min^2/ft^4 imperial).

The original style manufacture value agreed with other published fiberglass ducting manufacturer data. The original style manufacture value is also generally in-line with standard mining text data but is significantly lower than that quoted for “aged” ducting and from one published field test. The new duct manufacture k factor is less than all previously quoted values for fiberglass ducting. It is also approaching the highest theoretically derived values based upon standard surface roughness values; however that would be for fully turbulent rough pipe flow. This nearing agreement is in contrast to other ducting products where theoretical roughness values would indicate significantly lower k factor values than that typically quoted or measured.

Considering both resistance and leakage control play a significant role in system selection and relative economics, further studies are recommended to ascertain leakage coefficients for this style of ducting and whether size significantly affects k factor values.

DISCLAIMER

Any determination and/or reference made in this report with respect to any specific commercial product, process or service by trade name, trademark, manufacturer or otherwise shall be considered to be opinion; CanmetMINING makes no, and does not intend to make any, representations or implied warranties of merchantability or fitness for a particular purpose nor is it intended to endorse, recommend or favour any specific commercial product, process or service. The views and opinions of authors expressed herein do not necessarily state or reflect those of CanmetMINING and may not be used for advertising or product endorsement purposes.

CanmetMINING shall keep confidential and not disclose to third parties the information contained in or regarding this report for a period extending from the coming into force of this Agreement to five (5) years from the date of the termination or conclusion thereof, i.e. until June 30, 2020, except with the written consent of the CLIENT.

TABLE OF CONTENTS

TABLES

FIGURES

UNITS

The primary units used in this report are metric. However, as some mines still use imperial units in describing ventilation parameters, where appropriate, both units are given.

INTRODUCTION

CanmetMINING were asked to evaluate the performance of a new fibreglass ventilation duct manufactured by Schauenburg Industries Ltd. of North Bay, Ontario. This request arose out of the interest of the manufacturer and mining companies to have performance data namely a resistance to airflow value relating to this new manufacturing process product. The interest in establishing verified friction values for the new product was to support claims with respect to it being more energy efficient, and for comparison against other rigid ventilation ducting products in the same market space. The need for an expert assessment from CanmetMINING was financially supported by the National Research Council of Canada's Business Innovation Access Program (BIAP) as administered through their Industrial Research Assistance Program (IRAP).

The roughness of a ventilation duct's surface is one of many factors that have to be considered when designing a cost effective and efficient delivery or suction system. Quoted engineering values for absolute roughness of a surface are available for the various materials available, for example the average height of asperities for clean steel pipe can be 0.015 – 0.150 mm (0.0006 – 0.006 in) whereas PVC and plastic pipes are considerably smoother at 0.0015 – 0.0070 mm (0.0001 – 0.0003 in) [Engineering Toolbox, 2014], while fiberglass is within the same range being quoted as 0.0050 mm (0.0002 in) [AWWA, 2005]. Based upon standard fluid flow relationships, Colebrooke-White and Von Kármán, for the duct size tested, these would indicate a k factor of ~0.0011 – 0.0018 kg/m^3 (6.0 – 9.7 $\times 10^{-10}$ $lb•min^2/ft^4$ imperial), for hydraulically smooth pipe and rough pipe flow respectively under transitional turbulent and fully turbulent flow conditions. However, such theoretical values may not be representative of the systematic resistance of a duct system that includes joints at regular intervals. Furthermore although the flow is turbulent, for fully turbulent rough pipe flow Reynolds number, which characterizes the flow, would need to be very high in the order of 4×10^8 whereas actual test conditions were in the order of 1×10^6. Consequently the performance of such ducts trends more towards that of hydraulically smooth pipes.

Mine ventilation text books give higher values of the Atkinson friction, or k factor, for fiberglass ducting, namely 0.0024 kg/m^3 (13 $\times 10^{-10}$ $lb•min^2/ft^4$ imperial) [McPherson, 1993, MVSSA, 1992] and 0.0028 kg/m^3 (15 $\times 10^{-10}$ $lb•min^2/ft^4$ imperial) new, through to

0.0037 kg/m^3 (20 $\times$ 10^{-10} lb•min^2/ft^4 imperial) old, for the combined category of steel, wood and fiberglass ducting [Hartman, 1982]. Field evaluations of fiberglass duct have given in situ values of 0.0047 kg/m^3 (25 $\times$ 10^{-10} lb•min^2/ft^4 imperial) [Duckworth & Lowndes, 2003], while a fiberglass ducting manufacturer has stated 0.0022 kg/m^3 (12 $\times$ 10^{-10} lb•min^2/ft^4 imperial) [Schauenburg Flexadux Corporation, as reported in Duckworth & Lowndes, 2003]. However, except for the latter value, there is no information as to the actual finish of the duct's surface.

The products being tested in this study were manufactured with fiberglass spun onto a platen cylinder covered with either the traditional or new mylar product. The results of the two manufacturing methods were: the original product had a surface that was slightly rippled; whereas the newer product's surface was noticeably more uniform, with no rippling.

This assessment was based upon a test length assembled by Schauenburg Industries Ltd. at Hurley Ventilation Technologies (HVT) Inc.'s fan manufacturing and testing facility located in Greater Sudbury, Ontario. This location and establishment were chosen as HVT had the capacity to accommodate specific performance testing with a variable speed fan that permitted higher airflows, with respect to the duct size, than may typically be employed in a mine.

The performance testing of the two ducting styles involved measuring air volumes passing through a ~60 m (200 ft) long section of 0.61 m (2 ft) inside diameter (ID) duct and the associated pressure losses throughout its length. Both test ducts were constructed from 10 sections of ducting, each ~6.0 m (20 ft) long before assembly with a bell and spigot joint style. The slightly larger female end of each duct section also contained a rubber seal. The larger end and seal accommodated slow curves in the system and other minor deviations from a straight alignment. However, for the purpose of this testing, the duct system had been constructed with near perfect linear alignment. A prior inspection of the joint between two sections had shown neither noticeable changes in cross-sectional area nor any prominent end edges to cause additional resistance.

The test was designed such that high velocity flows would incur frictional pressure losses that could be confidently measured over a relatively short length of duct system, so permitting multiple independent measurements along the installation length. The surface location testing of the duct was also preferred as it could be assembled at a height that readily allowed unrestricted measurements. Whereas for an underground location, previous experience had shown the placement of such a duct adjacent to the back and/or against a side-wall, plus other access and mine operation logistics limited the quality and quantity of the measurements which could be taken. Duct installations in mines may also have aged and become coated in dust or the surface deteriorated due to exposure causing higher k values than when newly installed. Furthermore, the use of a duct installation assembled specifically for the test by the manufacturer would ensure that it had been constructed as per the manufacturer's requirements with respect to alignment and joint sealing. These considerations would help ensure that frictional pressure loss measurements were not compromised by bends, and that flow measurements were not adversely affected by leakage.

The trade-off of using a smaller size is that according to theory the relative roughness, and thereby the friction factor, of the duct would increase as it is related to the absolute roughness and diameter of the duct. Compared to 0.91-1.37 m (36 – 54 in) diameter ducts and using theoretical friction factor formulae for the same duct velocities, the resistance of a 0.61 m (24 in) diameter duct could respectively be 7 and 15% higher under fully turbulent flow. Similarly, according to theory the calculated friction factor could increase for lower velocities. Despite these potential differences, the trade–off using a smaller diameter shorter duct system was considered acceptable compared to using a much longer length system.

The airflow was measured indirectly using standard Pitot tube velocity traverse methods as well as directly using tracer gas. Barometric and differential pressures were measured with either an electronic barometer or a micro-manometer.

Additional measurements taken for the analysis included temperature and humidity, to determine the air density, and the distances between measurement points to calculate the frictional resistance of the duct to airflow.

Test Installation

Through consultation with Schauenburg Industries and HVT, a ~60 m (200 ft) nominal length by 0.61 m (24 in) ID auxiliary duct system was selected for evaluation using a model 28-18-3600 fan. The flow-pressure characteristic of this fan is shown in Figure 1.

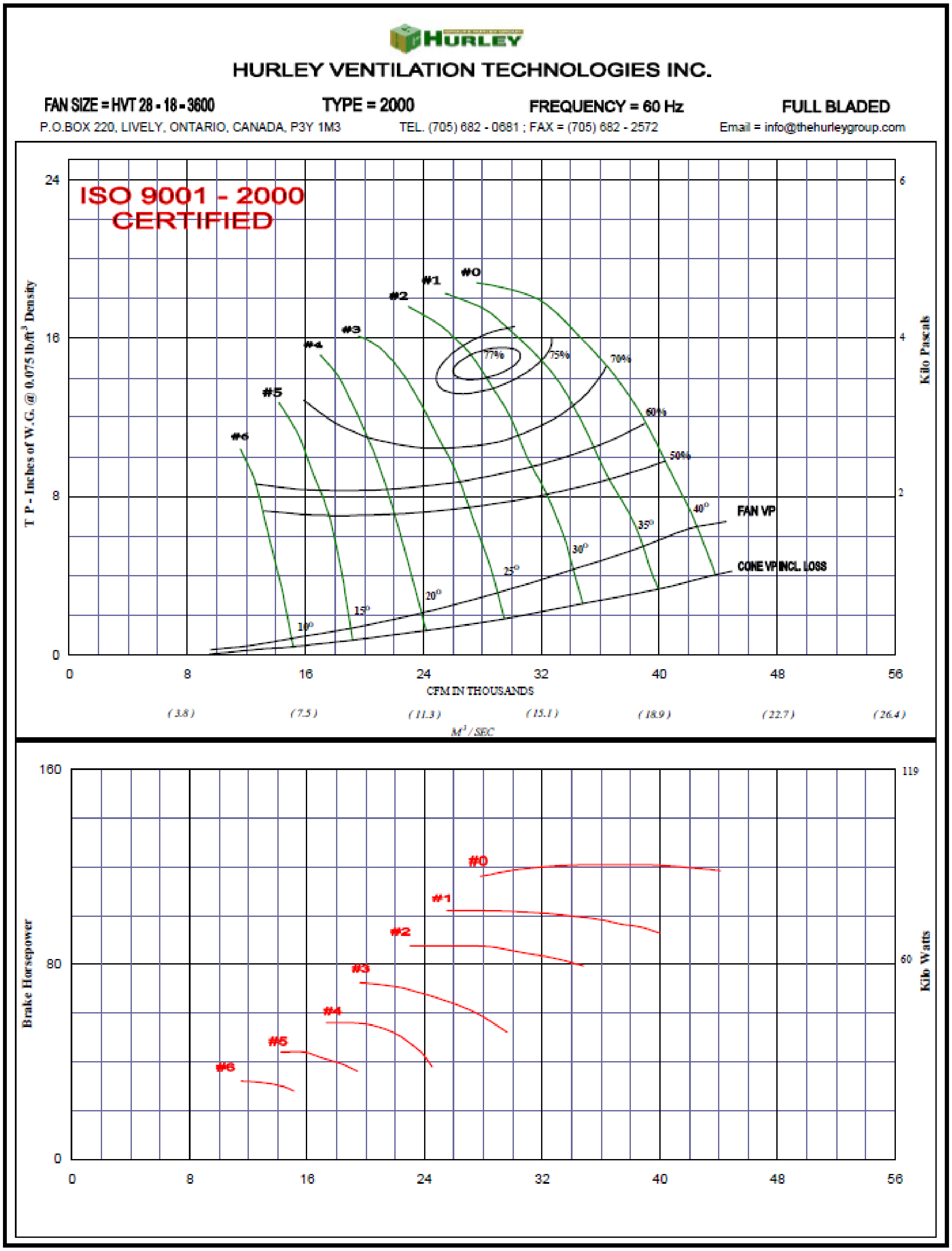

Figure 1 Fan performance characteristic curves

Figures 2 to 5 show the two ducts and associated features as assembled at the HVT facility. Figure 2 shows the fan connected to the 0.61 m (24 in) duct via a short transition, and the parallel duct assemblies at the test site. Figure 3 shows the exterior fastening between two sections and the optional wrap used to ensure minimal leakage. Figure 4 attempts to show the inner slightly rippled surface of the original style manufacture duct. Figure 5 similarly tries to show the smoother surface resulting from the newer manufacturing process for the duct, and the internal rubber gasket that forms the main seal between sections.

Procedures

The general flow equation used in mine ventilation calculations (Atkinson's Equation) is as follows:

$$p = k_{1.2} L \frac{per}{A^3} Q^2 \frac{\rho}{1.2} \qquad \text{Eqn (1)}$$

where: p = frictional pressure loss (Pa),

$k_{1.2}$ = Atkinson friction factor at standard density (kg/m^3),

L = length of airway (m),

per = perimeter of airway (m),

A = cross-sectional area of airway (m^2),

Q = airflow quantity (m^3/s),

ρ = measured air density (kg/m^3), and

1.2 = standard air density (kg/m^3).

In using the above equation, the perimeter and area values were based upon manufacturer supplied dimensions whereas the length was based upon field measurements. The perimeter and area of the duct/airway were determined from the supplied 0.61 m (24 in) internal diameter of the duct and assuming the duct was perfectly circular as 1.92 m (6.3 ft) and 0.29 m^2 (3.1 ft^2). The average length of the test measurement sections, between the mid-points of two adjacent duct sections, was confirmed with a measuring tape as 5.90 m (19.4 ft) and 5.88 m (19.3 ft) respectively for the old and new manufacturing process products.

Figure 2 Fan duct assembly at HVT facility

Figure 3 Jointing between two duct sections and optional wrap

Figure 4 Internal surface of old style manufacture duct

Figure 5 Internal surface of new style manufacture and the rubber sealing gasket

The air density within the duct under test was determined by using standard psychrometric relationships from the in-duct ambient dry-bulb temperature, the relative humidity of the air and the barometric pressure. For the duration of the testing, the air density did not vary significantly throughout the length of the duct or during the day, the average condition being 1.174 kg/m^3 (0.073 lb/ft^2).

The airflow was determined through two methods. A direct determination of the airflow was obtained through a tracer gas dilution method. It involves releasing a tracer gas (sulphur hexafluoride, SF_6) at a known constant rate into the airstream being evaluated. The technique then allowed the gas to fully mix with the airstream. Sampling the resultant mixture and then analyzing the concentration of the tracer gas in the air permits the direct determination of the volumetric flow rate. A simple calculation using the pure gas release rate (ml/min) and the final concentration (ppb), as measured with a gas chromatograph in a laboratory, provides the airflow directly independent of the duct shape or area. In this instance, the tracer gas was released into the intake of the fan, allowed to mix and then sampled at the discharge. Using this methodology, the airflow calculated from the release rate and duct discharge air samples is representative of the complete mixing point immediately downstream of the fan/gas release point as opposed to the discharge.

The other indirect method employed to determine the airflow was from averaged air velocity readings taken across a section of the duct. Here, the primary method was to measure the velocity pressure of the airflow at various points across the duct's cross-section, convert the velocity pressures to air velocities, determine the average air velocity and finally the airflow using the duct's cross-sectional area. This methodology although recognized as the "standard" is less direct, as in certain situations, measuring the cross-sectional area and using average air velocity can increase the uncertainty of the final result.

The average velocity in the duct at each measurement cross-sections was determined through an 8-point Pitot tube traverse performed across three diameters at 60° radial separation. Five measurement cross-sections, equally spaced along the length of the duct at approximately the mid-point of a duct segment, were used for the initial assessment of each duct, at the highest duty flow, to determine if there was any significant leakage. Upon showing minimal leakage, only three equally spaced measurements were used in the subsequent lower air speed assessment of each duct.

The methodology used was as per duct flow measurement standards, employed a log-Tchebycheff based distribution 8-point traverse with measurements at 0.021D (diameter), 0.117D, 0.184D, 0.345D, 0.655D, 0.816D, 0.883D and 0.979D relative distances along each diameter as per the American Society of Heating, Refrigerating and Air-Conditioning Engineers *Handbook* [ASHRAE, 2013]. The log-Tchebycheff spacing of measurement points is more accurate than an equal area based distribution, due to it taking wall friction and the fall-off of velocity near the walls into greater account. Three traverses were chosen to ensure the profile is essentially uniform across a cross-section. Whether, the profile was considered *ideal*, *good*, *satisfactory* or *unsatisfactory*, was based upon the individual velocity pressure (VP) measurements being greater than (VP_{max}/10) as per the American Conference of Governmental Industrial Hygienists *Industrial Ventilation* manual [ACGIH, 1988].

The locations of the measurement cross-sections, central to a duct length and initially downstream of the fan transition, were chosen to ensure that they were at least 7.5 diameters downstream and 3 diameters upstream of a major disturbance as per the *ASHRAE Handbook*, however a more common requirement of 10 diameters downstream was used. Also, the mid-point of a duct section was chosen to minimize the influence, if any, of the joints between each section. Based upon the segmental construction of the duct, the actual location of the first flow measurement traverse cross-section was >15D downstream of the fan. Excluding the fan/duct reducer transition, the location was >14D downstream of the cross-section change and the final fourth location was >5D upwind of the duct discharge. The spacing between the first through fifth traverse locations was every ~11.8 m (39 ft) (2 duct sections) or ~19D and double these values for the three traverse determinations.

The pressure loss per test section was determined from the difference between the internal/external static pressure readings taken at the ten measurement points along the duct. The external static pressures, taken at a common location, were also used to check and correct for changes in elevation or external pressure variations. The measurement of static pressure inside the duct, independent of any velocity component, was assured through using the “static” port of the Pitot tube at its centerline and ensuring the tube’s orientation with the flow inside the duct. Total pressure measurements, including the velocity component, were also taken for confirmation purposes. In this instance the barometer was connected to the “total” port of the Pitot tube, inserted to the centerline and again care was taken to ensure tube’s orientation with the flow inside the duct.

The cumulative static pressure losses were similarly determined with a digital manometer connected between two Pitot tubes inserted to the center and aligned with the flow in the duct. The cumulative losses were obtained by keeping one Pitot tube at the measurement point near the duct discharge and progressively advancing the other Pitot tube from the adjacent hole, repeatedly to the next hole progressing towards the fan. The sectional losses were then determined by difference.

With the fan in the forcing mode, the duct was assessed at two different air velocities by running the fan at full speed/flow with the variable frequency drive set to 60 Hz and then at ¾ flow and the fan controller set at 45 Hz.

Apparatus

The following instrumentation was used for the tracer gas methodology:

- A tracer gas (sulphur hexafluoride, SF_6) release comprising of a gas cylinder, a standard two-stage regulator, and a differential pressure regulator paired with a length of capillary tubing. In combination, this arrangement provides a very stable tracer gas release proportional to the length and bore of the capillary tubing for an applied pressure. The nominal release rate of the system was 80 ml/min, sufficient to provide the target diluted concentration of 100 – 200 ppb for subsequent analysis.
- A DryCal® DC-2 piston-type primary flow calibrator (Bios/Mesa Labs, Butler, New Jersey, USA) to determine the release rate.
- 30 cc polypropylene disposable syringes fitted with an air-tight cap to collect background and test point samples for post-study laboratory analysis.

The following instrumentation was used for the pressure methods:

- 2 standard Pitot tubes marked-up for a 1-point assessment of a 0.61 m (24 in) internal diameter duct.
- A Digiquartz® 745 digital barometer (Paroscientific, Redmond, Washington, USA) to assess the barometric pressure inside and outside of the duct at each measurement station.
- A DP Measurement TT Series electronic micro-manometer (DPM, Buckingham, UK) set to measure a differential pressure was used to determine cumulative pressure losses. The direct velocity measurement option was not selected to avoid the unit using a standard (surface) air density. This unit was connected to the Pitot tube to determine velocity pressures.
- A Vaisala HMI41/HMP45 temperature and humidity meter (Vaisala, Helsinki, Finland).

TEST RESULTS

The tests performed on the Schauenburg mine ventilation duct are described in relation to the schematic given in Figure 6.

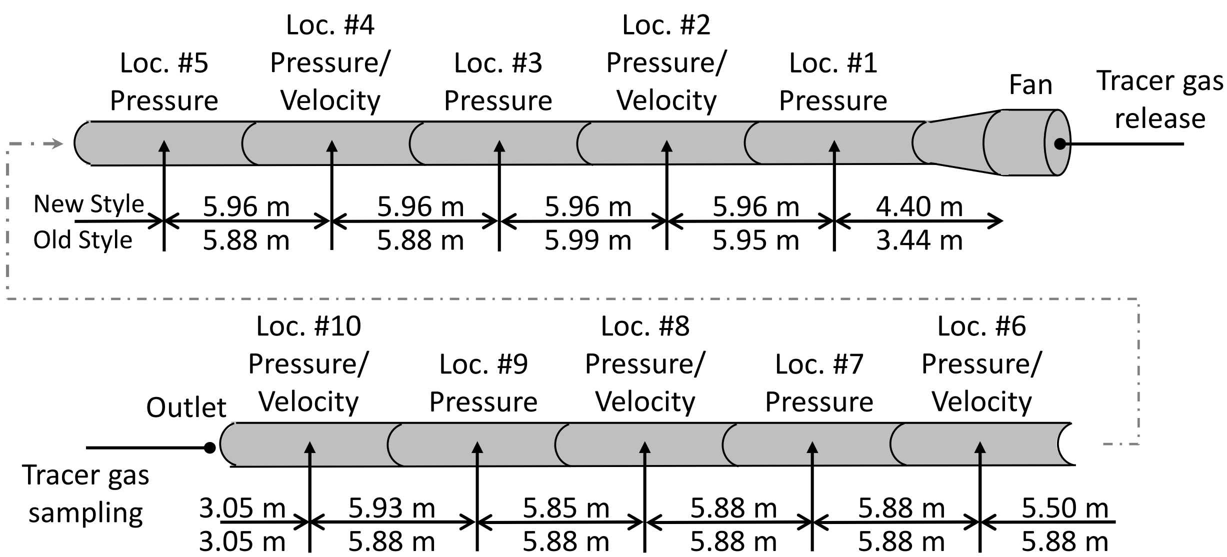

Figure 6 Duct test arrangement for the forcing tests

Flow Assessment – Forcing (Blowing) Mode

Under the forcing arrangement of the fan, the direction of flow within the duct installation was as per manufacturer specifications namely in-line with the joint insertion orientation. This requirement was specified to reduce any shock loss influence of the male-end of the duct to the flow. Figure 7 provides a sample of the Pitot tube traverse results in terms of velocity pressure and velocity. This figure shows that the three measured airflow profiles can be considered ideal with all the values being positive and meeting the condition $>VP_{max}/10$, they also show the consistency of the profile across the three test diameters.

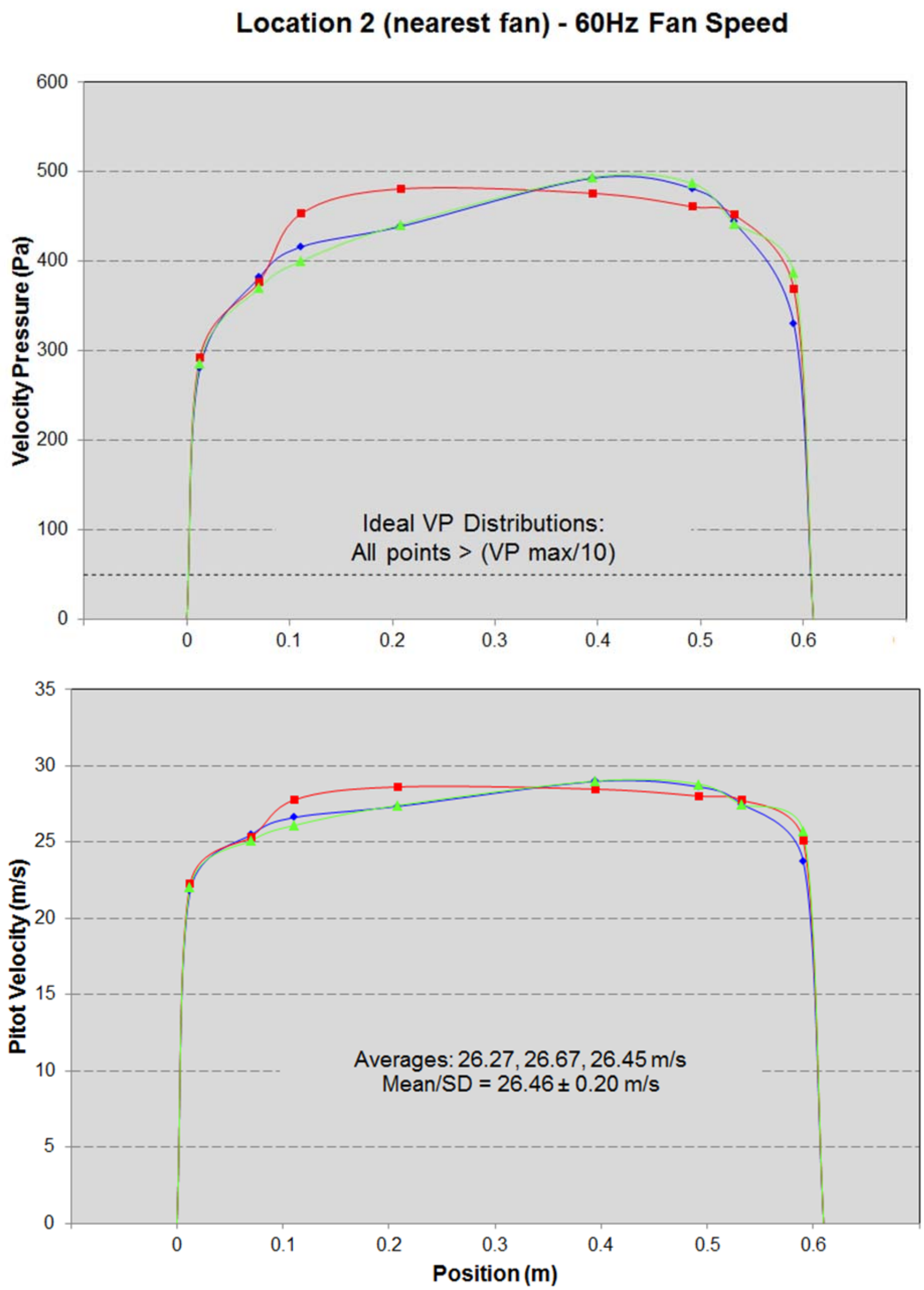

Figure 7 Velocity pressure and velocity profiles obtained from a Pitot tube traverse

The velocity profiles specifically show that the majority of the cross-section contains air at a high velocity, for the most part in the 22 – 29 m/s (~4300 – 5700 fpm) range and then rapidly tailing off to lower velocities at the walls. Similar profiles were observed across all measurement locations for both duct systems and each fan speed.

Table 1 & Table 2 summarize the Pitot tube results for the three traverses at each of the five measurement locations, as well as overall, for the two speed trials of each duct with the fan blowing into the duct. These results show the overall consistency of the flow throughout the full length of the duct for each test scenario indicating there were negligible losses. However, the maximum differential pressure, close to the fan, available to generate leakage only ranged from 240 – 530 Pa (1.0 – 2.1 "wg) across the low and high flow conditions for both ducts.

The 25% reduction in velocity and flow for each duct style were also in line with the fan speed reduction from 60 to 45 Hz.

The associated tracer gas determinations of airflow for each of the tests were 9.27 ± 0.45 m^3/s (19.6 ± 0.9 kcfm) for the new duct with the fan at 60 Hz; 5.66 ± 0.28 m^3/s (12.0 ± 0.6 kcfm) for the new duct with the fan at 45 Hz; 7.64 ± 0.28 m^3/s (16.2 ± 0.6 kcfm) for the old duct with the fan at 60 Hz; and 5.50 ± 0.61 m^3/s (11.7 ± 1.3 kcfm) for the old duct with the fan at 45 Hz. Apart from the first tracer gas airflow determination, that appears to be anomalous, the differences of 1 to 5%, well within the standard deviation of the results, show there was good agreement between the pitot-traverses and other three tracer gas results.

Table 1 Summary of velocity measurement analyses – new manufacture process

Fan Speed, Duct Type	Pitot-tube traverse detail			Three Diameter Traverse Averages									
				Location 2 (Fan)		Location 4		Location 6		Location 8		Location 10 (Discharge)	
	Point	Relative Location (Diameters)	Distance from wall (m)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)
60 Hz New Style	1	0.021	0.013	286	22.07	329	23.65	324	23.48	286	22.03	315	23.14
	2	0.117	0.071	376	25.32	433	27.15	439	27.34	370	25.11	401	26.14
	3	0.184	0.112	423	26.84	480	28.59	491	28.92	424	26.86	442	27.45
	4	0.345	0.210	454	27.79	508	29.41	526	29.94	481	28.63	513	29.55
	5	0.655	0.399	488	28.82	452	27.74	482	28.66	523	29.85	507	29.40
	6	0.816	0.497	476	28.48	397	25.97	420	26.74	471	28.34	447	27.59
	7	0.883	0.538	446	27.56	382	25.49	376	25.29	424	26.86	404	26.23
	8	0.979	0.597	362	24.82	310	22.93	282	21.90	337	23.97	295	22.37
	Indiividual cross-sections			Average	SD (±)	Average	SD (±)	Average	SD (±)	Average	SD (±)	Average	SD (±)
		Velocity,v (m/s)		26.46	0.20	26.37	0.31	26.53	0.20	26.46	0.38	26.48	0.44
		Quantiity,Q (m^3/s)		7.73	0.06	7.70	0.09	7.75	0.06	7.72	0.11	7.73	0.13
	Duct			Average					SD (±)				
		Velocity,v (m/s)		26.46					0.30				
		Quantiity,Q (m^3/s)		7.73					0.09				
45 Hz New Style	1	0.021	0.013	197	18.25			200	18.42			178	17.39
	2	0.117	0.071	241	20.23			235	19.97			230	19.81
	3	0.184	0.112	268	21.36			271	21.47			260	21.04
	4	0.345	0.210	277	21.71			296	22.44			298	22.52
	5	0.655	0.399	263	21.15			281	21.88			304	22.75
	6	0.816	0.497	261	21.07			253	20.75			263	21.15
	7	0.883	0.538	246	20.44			234	19.93			237	20.09
	8	0.979	0.597	192	18.03			182	17.53			174	17.20
	Indiividual cross-sections			Average	SD (±)			Average	SD (±)			Average	SD (±)
		Velocity,v (m/s)		20.28	0.34			20.30	0.05			20.24	0.28
		Quantiity,Q (m3/s)		5.92	0.10			5.93	0.01			5.91	0.08
	Duct			Average					SD (±)				
		Velocity,v (m/s)		20.27					0.22				
		Quantiity,Q (m3/s)		5.92					0.07				

Table 2 Summary of velocity measurement analyses – old manufacture process

Fan Speed, Duct Type	Pitot-tube traverse detail			Three Diameter Traverse Averages									
				Location 2		Location 4		Location 6		Location 8		Location 10	
	Point	Relative Location (Diameters	Distance from wall (m)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)	Velocity Pressure, Vp (Pa)	Velocity, v (m/s)
60 Hz Old Style	1	0.021	0.013	299	22.51	275	21.52	254	20.70	298	22.47	309	22.92
	2	0.117	0.071	387	25.67	356	24.62	385	25.61	340	23.99	357	24.65
	3	0.184	0.112	446	27.57	410	26.41	433	27.16	429	27.03	424	26.86
	4	0.345	0.210	477	28.50	453	27.78	484	28.70	510	29.48	496	29.07
	5	0.655	0.399	449	27.64	507	29.38	470	28.28	495	29.04	502	29.25
	6	0.816	0.497	432	27.12	466	28.17	425	26.90	438	27.31	446	27.57
	7	0.883	0.538	384	25.56	417	26.66	376	25.31	396	25.96	402	26.17
	8	0.979	0.597	302	22.66	301	22.63	289	22.20	259	20.93	312	23.03
	Indiividual cross-sections			Average	SD (±)	Average	SD (±)	Average	SD (±)	Average	SD (±)	Average	SD (±)
		Velocity,v (m/s)		25.90	0.75	25.90	0.62	25.61	0.39	25.78	0.77	26.19	0.29
		Quantiity,Q (m^3/s)		7.56	0.22	7.56	0.18	7.48	0.11	7.53	0.23	7.65	0.08
	Duct			Average					SD (±)				
		Velocity,v (m/s)		25.88					0.56				
		Quantiity,Q (m^3/s)		7.56					0.16				
45 Hz Old Style	1	0.021	0.013	176	17.26			179	17.44			200	18.41
	2	0.117	0.071	234	19.96			215	19.15			215	19.15
	3	0.184	0.112	259	21.00			256	20.87			253	20.75
	4	0.345	0.210	274	21.60			283	21.94			292	22.30
	5	0.655	0.399	272	21.54			285	22.02			300	22.59
	6	0.816	0.497	251	20.66			244	20.40			258	20.95
	7	0.883	0.538	231	19.82			219	19.31			220	19.36
	8	0.979	0.597	176	17.27			152	16.06			161	16.52
	Indiividual cross-sections			Average	SD (±)			Average	SD (±)			Average	SD (±)
		Velocity,v (m/s)		19.89	0.56			19.65	0.28			20.00	0.45
		Quantiity,Q (m3/s)		5.81	0.16			5.74	0.08			5.84	0.13
	Duct			Average					SD (±)				
		Velocity,v (m/s)		19.85					0.43				
		Quantiity,Q (m3/s)		5.79					0.13				

Pressure Assessment – Forcing Mode

The primary method used to determine pressure losses per section was the difference between Pitot tube static pressure readings taken with a digital barometer at each of ten measurement points along the duct system. These barometer values were corrected for any ambient drift and change in elevation. Confirmation measurements were taken using total pressure again with a barometer, and then from the difference between cumulative static pressure measurements taken with a digital manometer. The results from these measurements across the two fan speed settings for the two duct manufacturing styles are summarized in Table 3.

Comparing the common speed results, at 60 Hz, Table 3 shows the average pressure loss per section based upon barometer static pressure measurements was 44.8 ± 12.7 Pa (0.18 ± 0.05 "wg) at a flow of 7.73 ± 0.09 m^3/s (16.4 ± 0.2 kcfm) for the new style duct, and notably greater at 57.8 ± 10.4 Pa (0.23 ± 0.04 "wg) at a flow of 7.56 ± 0.16 m^3/s (16.0 ± 0.3 kcfm) for the old style duct. At the lower fan speed and flow, the new duct style again created less frictional losses than the old style manufacturer for a comparable flow. However, the difference was not as significant.

The average static pressure losses per individual section derived by the manometer method were comparable to the barometer but slightly more variable.

For the most part the pressure losses derived from total pressure measurements were again comparable but generally had the highest variability. Throughout, the values for the first section closest to the fan appeared to be anomalous; this is believed to be due to the invalid assumption of the center-point velocity pressure being constant throughout the length of the duct as may be expected for the constant flowrate. Although not measured, the results tend to indicate that the profile may not have been sufficiently developed at the first measurement point, compared to the second where the first flow traverse was performed. In regard to the actual measurements, it should also be noted that the total pressure method, due to including the velocity component, would have been more susceptible to misalignment effects.

Table 3 Summary of pressure measurements and loss assessment

Fan Speed/ Duct	Instrument/ Method	Pressure Type	Fan	Duct Section (From - To)									Discharge	Duct Combined Loss		Sectional Loss	
				#1 - #2	#2 - #3	#3 - #4	#4 - #5	#5 - #6	#6 - #7	#7 - #8	#8 - #9	#9 - #10		#1 - #10	#2 - #10	Average	SD
				(Pa)	(Pa)	(Pa)	(Pa)	(Pa)	(Pa)	(Pa)	(Pa)	(Pa)		(Pa)	(Pa)	(Pa)	(Pa)
60Hz New Style	Barometer	Static		47.2	42.2	42.8	48.0	58.4	27.1	66.7	28.0	43.2		403.6	356.4	44.8	12.7
	Point x Point	Total		*(12.6)*	44.8	45.8	60.5	13.8	45.6	55.8	49.7	41.8			357.6	44.7	14.0
	Manometer Cumulative	Static		65.0	31.0	47.0	42.0	58.0	18.0	71.0	43.0	60.0		435.0	370.0	46.3	16.9
45Hz New Style	Barometer	Static		29.7	33.7	21.2	39.5	27.5	19.1	30.4	25.2	32.1		258.5	228.8	28.7	6.3
	Point x Point	Total		*(7.6)*	26.1	17.8	26.1	9.3	43.0	35.3	25.1	36.3			219.1	27.4	10.8
	Manometer Cumulative	Static		12.0	21.0	35.0	37.0	20.0	18.0	40.0	31.0	30.0		244.0	232.0	29.0	8.4
60Hz Old Style	Barometer	Static		64.1	67.6	53.2	51.8	60.0	55.2	69.8	35.5	62.5		519.8	455.7	57.8	10.4
	Point x Point	Total		*(24.3)*	51.5	31.9	55.5	62.2	55.0	37.9	47.4	54.9			396.3	49.5	10.1
	Manometer Cumulative	Static		60.0	80.0	52.0	30.0	77.0	59.0	66.0	65.0	41.0		530.0	470.0	58.8	17.2
45Hz Old Style	Barometer	Static		36.0	45.6	31.7	31.4	37.2	20.6	34.4	33.4	34.8		305.0	269.0	33.9	6.5
	Point x Point	Total		*(24.7)*	31.9	28.9	23.0	22.0	24.9	32.8	30.8	29.1			223.5	27.9	4.1
	Manometer Cumulative	Static		34.0	32.0	28.0	33.0	30.0	39.0	30.0	37.0	31.0		294.0	260.0	32.5	3.7
New	Distance (m)		4.40	5.96	5.96	5.96	5.96	5.55	5.88	5.88	5.85	5.93	3.05	Avg./SD	5.88	0.13	
Old	Distance (m)		3.44	5.95	5.99	5.88	5.88	5.88	5.88	5.88	5.88	5.88	3.05	Avg./SD	5.90	0.04	

Duct Resistance/k Factor Assessment – Forcing Mode

The average length of each test section for the new and old styles were 5.88 ± 0.13 m (19.3 ± 0.4 ft) and 5.90 ± 0.04 m (19.4 ± 0.1 ft), comprising two (2) duct ½ length sections and one (1) joint (see Figure 6). The cross-sectional area calculated from a diameter of 0.61 m (2.0 ft) was 0.29 m^2 (3.1 ft^2). The average air density inside the duct was 1.17 kg/m^3 (0.073 lb/ft^2).

From using Equation 1, the above dimensional data, air density and the average airflows and average barometer static pressure losses per test section, including a joint, the average Atkinson friction factor from nine measurements, at standard air density was determined to be:

For the new duct style,

- 0.00168 ± 0.00055 kg/m^3 for the high speed test, and
- 0.00184 ± 0.00047 kg/m^3 for the low speed test.
- The average imperial equivalent would be k = 9.5 ± 2 $\times$ 10^{-10} lb•min^2/ft^4.

For the old duct style,

- 0.00227 ± 0.00048 kg/m^3 for the high speed test, and
- 0.00226 ± 0.00051 kg/m^3 for the low speed test.
- The average imperial equivalent would be k = 12.2 ± 2 $\times$ 10^{-10} lb•min^2/ft^4.

In the above determination, the difference in k factor for the measured air density as opposed to standard air density was negligible. The Atkinson friction factor is referenced at standard density purely to allow for its easier correction under other conditions such as in deep mines.

The tolerance in the above determinations is a result of the variability of the pressure losses between the ten measurement locations, see Table 3. In part, the high tolerance relative to the values determined are a function of the small pressure losses measured between each pair of measurement locations and the stability/accuracy of these small pressure measurements. In the design of this study, one of the objectives was to maximize the flow through the duct system in order to provide the greatest losses possible and thereby greater confidence in the measurement of losses and definition of the resistance.

Considering that there were negligible losses, if any, from the duct system throughout the testing, an overall k factor can be also determined from the combined loss through the duct using a regression analysis. This treatment also limits the influence of outliers that may bias the standard deviations used with the previous simple pressure loss averages.

Figure 8 shows a linear regression analysis of the static pressure difference to atmosphere, as measured at Locations #1 through #10 for each of the two fan controller speed settings for the new style duct. In the "y = mx + c" equations defining the pressure distance relationship, the "m" terms is the pressure loss per unit distance (or meter length). Figure 9 shows a similar regression treatment of the static pressure differences between two measurement locations within the duct of increasing length, i.e. that between Locations #9 & #10, through to that between Locations #1 & #10. Figure 10 and Figure 11 similarly show the regression analyses of the barometer and manometer results respectively for the old style of duct. All of these figures show the high linearity of the results with R^2 values $\geq$ 0.99.

Using the regression gradients and the associated flows the Atkinson friction factors derived for the new duct style at standard air density were determined to be:

- 0.00173 ± 0.00009 kg/m^3 for the high speed test based upon barometry,
- 0.00172 ± 0.00008 kg/m^3 for the high speed test based upon manometry,
- 0.00184 ± 0.00008 kg/m^3 for the low speed test based upon barometry, and
- 0.00178 ± 0.00010 kg/m^3 for the low speed test based upon manometry.
- The overall average was 0.00177 ± 0.00009 kg/m^3.
- The average imperial equivalent would be k = 9.5 ± 0.5 $\times$ 10^{-10} lb•min^2/ft^4.

Considering the tolerances, these four determinations for the new duct produce the same k factor result.

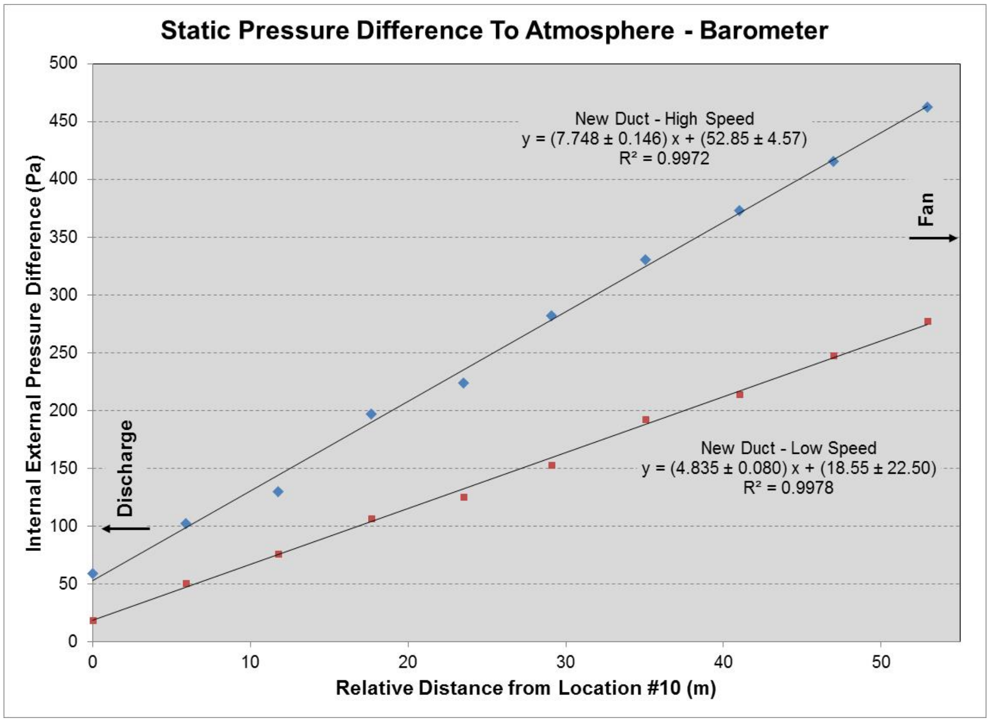

Figure 8 Static pressure loss profile of new style ducting from barometer measurements for high and low speed settings

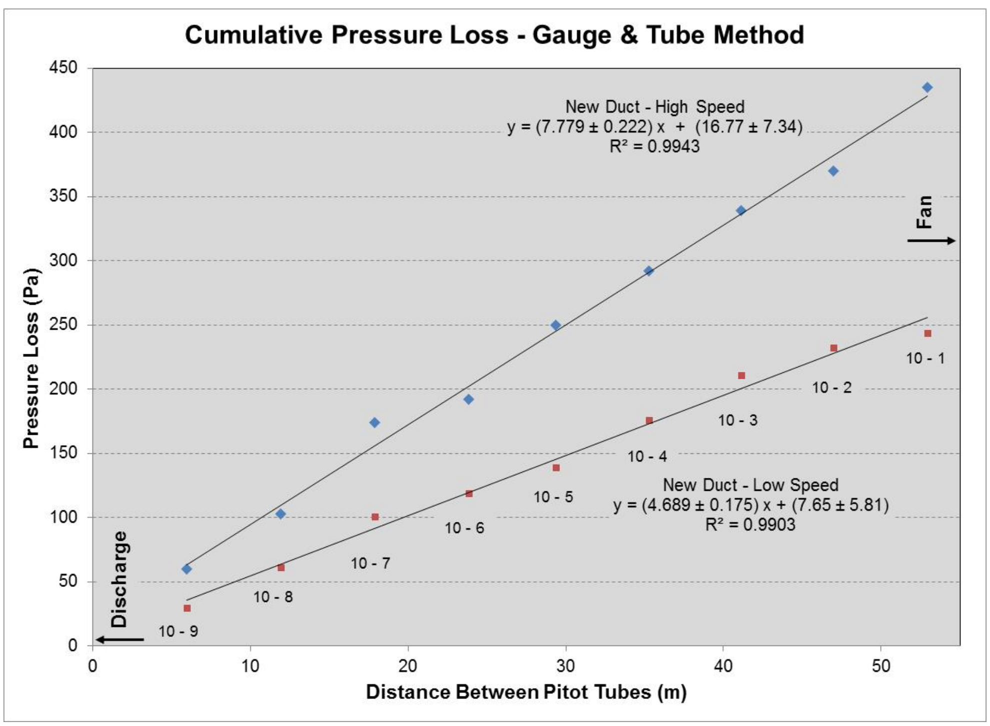

Figure 9 Static pressure loss profile of new style ducting from manometer gauge and tube measurements at the high and low speed settings

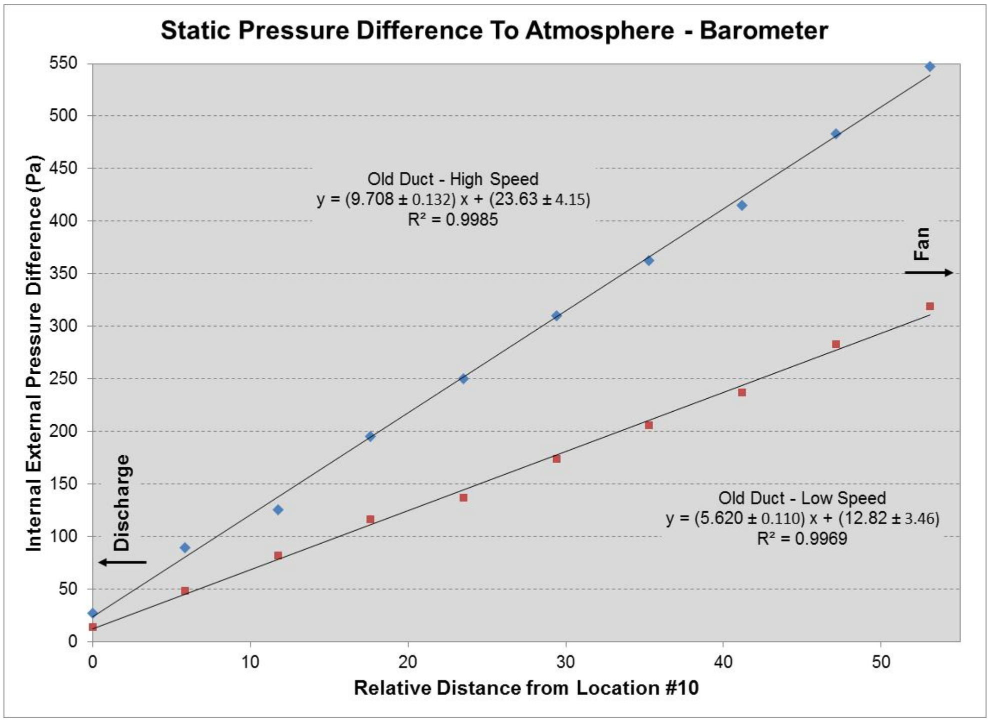

Figure 10 Static pressure loss profile of old style ducting from barometer measurements for high and low speed settings

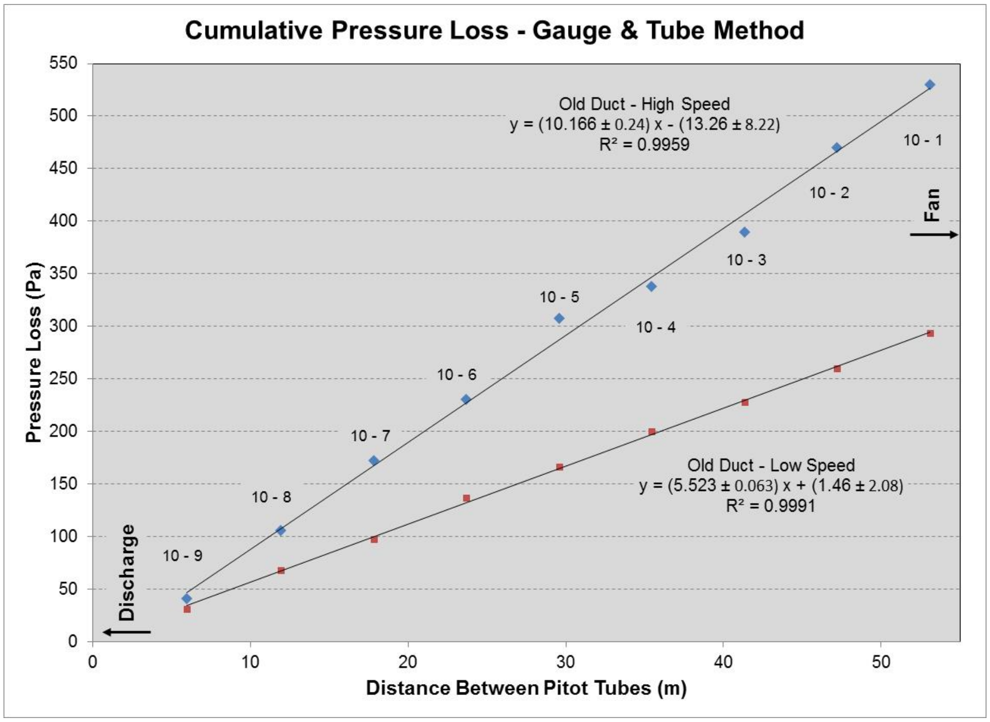

Figure 11 Static pressure loss profile of new style ducting from manometer gauge and tube measurements at the high and low speed settings

Similarly, the regression analysis based Atkinson friction factors for the old duct style were:

- 0.00226 ± 0.00013 kg/m^3 for the high speed test based upon barometry,
- 0.00237 ± 0.00015 kg/m^3 for the high speed test based upon manometry,
- 0.00223 ± 0.00015 kg/m^3 for the low speed test based upon barometry, and
- 0.00219 ± 0.00015 kg/m^3 for the low speed test based upon manometry. The overall average was 0.00226 ± 0.00015 kg/m^3.
- The average imperial equivalent would be k = 12.2 ± 0.8 $\times 10^{-10}$ $lb•min^2/ft^4$.

Again, the disagreement between the four determinations is within the deviation of the individual results. This value obtained for the old style duct is also consistent with the 0.0022 kg/m^3 (12 $\times 10^{-10}$ $lb•min^2/ft^4$ imperial), referenced by Schauenburg Flexadux of the USA in Duckworth & Lowndes [2003].

These test results show an average reduction of the duct's resistance of 22% with the new manufacturing process.

DISCUSSION

The design of the test, using a small diameter duct (~0.6 m, (24 in)) to maximize air velocity, was successful in that it allowed multiple measurements, up to 9, to be made along a relatively short length of duct (~60 m, (200 ft)).

The testing of a surface installation specifically assembled for the test ensured its construction, namely tightness of joints and alignment, were as per manufacturer specifications for optimum performance and to minimize leakage. The use of new duct also removed any age-related effects from exposure to underground mining conditions.

Throughout each of the four duct/flow scenarios used, the flow throughout the duct's length was consistent and any leakage occurring was too small to be measurable. However, the maximum driving pressure to cause leakage only reached 530 Pa (2.1 "wg).

The overall pressure losses measured along the full duct (over ~53 m (175 ft)) were also found to be consistent; the average standard deviation between the static pressure determination of the barometer and manometer, across the four test scenarios was ±3.3%. Upon discounting the first total pressure measurement at Location #1, the consistency of the pressure losses along ~47 m (155 ft) extended across all three static and total pressure methods with an average standard deviation of ±2.1%. The total pressure values measured at Location #1 were discounted as they generated suspect losses across all four scenarios, probably a result of the velocity profile at this location closest to the fan not being fully developed.

Although the average results were comparable, there was notable variation within the nine sectional losses determined from the static pressure values measured with the barometer for each test scenario. The variation in the sectional values, in part, may be attributable to the time/elevation based adjustments derived from reference pressures. In certain instances, these corrections on average 3.8 ± 2.5 Pa (0.015 ± 0.010 ”wg), ranged from 0.1 – 9 Pa (0.0004 – 0.04 ”wg). The latter, if not fully appropriate, would be a significant correction in sectional losses that ranged from ~30 – 60 Pa (0.1 – 0.2 ”wg) across the four scenarios. In contrast, any correction to the full system losses, ranging from ~250 – 520 Pa (1.0 – 2.1 ”wg), would be less significant. Consequently, greater weight may be given to the full system derived resistances, while the sectional derivation provides an indication of how a single reading, if taken in isolation, can provide an erroneous resistance value. This is further supported by the regression based assessment of the whole duct where the overall resistance values were in much closer agreement with smaller standard deviations.

The resistance of the two styles (old and new) of 0.61 m (24 in) diameter x ~6.0 m (20 ft) section length fiberglass ducting produced by Schauenburg Industries as measured at two airspeeds over a 60 m (200 ft) long system were as follows:

For the new duct style,

- 0.00176 ± 0.00051 kg/m^3 per section, and
- 0.00177 ± 0.00009 kg/m^3 over the full measured length.
- The imperial equivalent would be k = $9.5 \pm 0.5 \times 10^{-10}$ $lb \cdot min^2/ft^4$.

For the old duct style,

- 0.00227 ± 0.00050 kg/m^3 per section, and
- 0.00226 ± 0.00015 kg/m^3 over the full measured length.
- The imperial equivalent would be k = 12.2 ± 0.8 $\times$ 10^{-10} $lb•min^2/ft^4$.

Generally, these values are higher than theory might predict. However, the same can also be said for all common duct material types. The value obtained for the original manufacturing style of duct, although notably higher than the ~0.0012 – 0.0018 kg/m^3 theoretically derived range, is comparable with historically given values. The value obtained for the new duct manufacture process is at the upper limit of the theoretical range.

For the most part the results obtained in this testing show the fiberglass ducting to have a resistance equal or less than the 0.0024-0.0028 kg/m^3 quoted for clean duct by McPherson, [1993], MVSSA, [1992] and Hartman [1982] in standard mine ventilation texts; and notably lower than the “aged” value 0.037 kg/m^3 value reported by Hartman [1982] and that of 0.0047 kg/m^3 from field testing of Duckworth & Lowndes [2003]. However, little or no detail is available as to what size ducting was used in their derivation.

Considering the size tested here, may be small compared to that typically used, these equal or better results would tend to indicate that there are no significant size related effects pertaining to any cross-sectional area variations (i.e. a minor contraction or other shock loss) through a duct joint.

According to pipe/duct flow theory, the k factor resistance should decrease for larger diameter ducts for comparable air velocities. However, due to differences between theory and generally accepted values and actual test results for ventilation ducting this cannot be confirmed.

Potential Energy Savings

Based upon the results of the testing performed at HVT using the 0.61 m (24 in) ID fiberglass ducting, the new manufacturing process reduced the measured k factor by 22%.

Assuming the old and new style ducting were used to deliver the same flow, the frictional losses through the duct and needs from a fan would similarly be reduced by 22%. However, systematic pressure savings would be tempered by inlet losses (accelerating the air), losses through the fan (or fans), and then losses at the duct discharge. All are velocity related.

Recommendations for Further Work

The overall performance and selection of a fan/duct air delivery system is dependent on many factors. Although the resistance to flow is important, leakage potential is another prime decision criterion because it can significantly degrade the system's performance. Consequently, it is highly recommended that the company consider obtaining comparative leakage data for their new and old duct manufacturing styles.

To add greater confidence to the values obtained at the HVT facility and or show any sizing effect, testing a larger diameter duct with a proportionally higher flow and longer duct length may be warranted.

It can also be expected that the end-user, the mining industry, would be interested to know how results obtained under ideal conditions compare to a more typical installations where non-alignment may affect both resistance and leakage.

CONCLUSIONS

The test arrangement allowed nine measurements of pressure loss and up to five measurements of flow along the length of the duct system. The static pressure and velocity profile assessments produced consistent results in terms of pressure loss and flow throughout the tested ~60 m (200 ft) length for each of the two 0.61 m (24 in) diameter fiberglass duct manufacturing styles, from Schauenburg Industries Ltd., under the two test speed conditions.

The results for the full tested length, showed the old style manufactured duct to have a systematic friction (k) factor (friction plus any shock losses at the joints if present) of 0.00226 ± 0.00015 kg/m^3 (or 12.2 ± 0.8 $\times$ 10^{-10} $lb{\bullet}min^2/ft^4$ imperial) while the new style manufacture had decreased the k factor to 0.00177 ± 0.00009 kg/m^3 (or 9.5 ± 0.5 $\times$ 10^{-10} $lb{\bullet}min^2/ft^4$ imperial). The sectional results per duct section supported these same values but were prone to higher tolerances introduced by the methodology employed. The old style value agrees with that put out by ducting manufacturers.

Considering the duct installation was straight and a visual inspection of the male/female insertion joint of two sections, it is believed that these values are a true reflection of the resistance of the duct surface and any influence, shock loss, introduced by the joints would have been negligible. The new fiberglass ducting values, unlike other duct materials, are now comparable with the upper limit of theoretically derived values based upon the height of surface roughness.

Due to the short length of the duct and nature of this test not exhibiting any measurable leakage, further work to establish leakage values is highly recommended.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Hurley Ventilation Technology (HVT) for making their facility available, including the supply of a fan and an operator for this testing.

REFERENCES

ACGIH, 1988, *Industrial Ventilation: A manual of recommended practice*, 20th Edition, ISBN 0-936712-79-1.

ASHRAE, 2013, *2013 ASHRAE® Handbook: Fundamentals*, ISBN 978-1-936504-45-9.

American Water Works Association (AWWA), 2005. *Fiberglass Pipe Design*. Second edition. Denver, CO: American Water Works Association.

Duckworth, I.J. and Lowndes, I.S., 2003. *Modelling of auxiliary ventilation systems* Transactions of the Institution of Mining and Metallurgy: Section A., Mining Technology. 112(2), 105-113.

Engineering Toolbox, 2014. *Roughness & Surface Coefficients of Ventilation Ducts*, http://www.engineeringtoolbox.com/surface-roughness-ventilation-ducts-d_209.html, as accessed June 2, 2015.

Hartman, 1982. *Mine Ventilation and Air Conditioning*, 2nd Edition, ISBN 0-89464-471-8.

McPherson, 1993. *Subsurface Ventilation and Environmental Engineering*, 1st Edition. London; Chapman and Hall.

MVSSA, 1992. *The Mine Ventilation Practitioner's Data Book*, Mine Ventilation Society of South Africa, Johannesburg.