Quantifying assemblage losses in auxiliary ventilation systems

E. De Souza
AirFinders Inc., Kingston, Canada

ABSTRACT: While mine ventilation systems may account for 40% to 50% of the energy consumption of a mine operation, auxiliary ventilation alone may be accountable for half of this consumption. In effect, auxiliary ventilation systems comprise a significant portion of a mine operation's base energy demand and is consequently responsible for a large percentage of the total mine operating costs. This paper presents how engineering design principles can be applied to design efficient and reliable auxiliary ventilation systems, especially focusing on assemblage losses. Case studies are presented to demonstrate the effect of design, installation and maintenance practices on system reliability and operating costs. In particular, the effect of assemblage losses is quantified in terms of operating efficiencies, energy consumption and costs.

1 INTRODUCTION

Increasing costs of electricity have resulted in emphasis on energy-efficient designs and operation for all energy-consuming systems in mining. Since ventilation systems normally account for 25-40% of the total energy costs and 40-50% of the electrical consumption of a mine operation (De Souza, 2018, 2013), the optimization of ventilation systems is today a ventilation engineer's top priority.

While modern duct-fan systems require precise engineering design, meticulous attention to installation and regular maintenance practices, many installations are often designed based on outdated rules of thumb and with disregard to best installation practices. In the course of many years of investigations of duct-fan systems, the author has found them to be, in general, fairly energy inefficient, with many systems operating at efficiencies below 65% and with air leakages ranging between 25% and 75% (De Souza, 2004).

Auxiliary ventilation systems comprise a significant portion of a mine operation's base energy demand and may be accountable for half of a mine ventilation system energy consumption. Typical auxiliary ventilation systems are fairly energy inefficient; factors affecting mechanical and ventilation efficiencies loss include design flaws, installation practices and air leakage.

General solutions and tactics for improving auxiliary ventilation systems as presented in this paper come from multiple ventilation audits performed by the author. They target sub-system components which affect shock losses and mechanical and ventilation efficiencies. By increasing the efficiency of auxiliary ventilation system components and by correcting inappropriate designs or system degradation caused by poor maintenance, the overall capacity of the system in delivering air to the required active faces can often be improved.

2 CASE APPLICATION

A case application associated with extensive engineering work conducted by the author is presented in this section to demonstrate how, by conducting detailed ventilation efficiency audits, simple low-cost solutions can be devised to increase efficiency, reduce power consumption, and lower operating costs.

The case study is based on the auxiliary ventilation system illustrated in Figure 1. A series of analysis are performed to quantify the contribution of each component of the complete system to energy consumption and costs: inlet bell, screen, silencers, system friction, couplings, bends, duct exit. The effect of air leakage and of installation practices is also quantified. The analysis was based on analytical procedures and scientific guidelines developed by the author (De Souza & Dirige, 2022) and use of specialized software (AirFinders, 2022).

The auxiliary ventilation system, to be installed in a development drift to supply 18.88 m^3/s air for a diesel production fleet rated at 298.3 kW, has the following design characteristics:

- layflat duct - new, 1.2192 m diameter, provided in 15.24 m long sections, 10 sections of ducting. Multi clip joints.
- spiral duct, new, 1.2192 m diameter, 1 section 15.24 m for bend. Multi clip joints.
- total column length - 167.64 m.
- fan: 1.219-0.80-1780 (fan diameter-hub diameter-rpm) with a 149.14 kW motor. 600 V. Motor efficiency 95%. Power factor 0.84.
- inlet bell - 1.651 m diameter, 0.2159 m long.
- screen - wire mesh screen of 95% net free area.
- silencers - two podless flow through silencers.
- bend - right angle normal bend of 1.524 m radius.
- cost of power: $0.08/ kW.hr.
- operation - 24 hours/day, 365 days/year.
- standard density conditions.

Three cases, with operational features presented in Table 1, are considered. Case 1 represents the system design to meet the flow requirements of at the face of 18.88 m^3/s and considers a design air leakage of 20%. The fan supply flow is 23.6 m^3/s. An ‘installation quality factor’ of 10%, representing a ‘good’ installation, is used to adjust the system static resistance pressure. Case 2 represents the system as installed. Attained flows at the face of 15.56 m^3/s do not meet requirements, and is based on an air leakage of 30%. The fan supply flow is 22.23 m^3/s. An ‘installation quality factor’ of 30%, representing a ‘poor’ installation, is used. Case 3 represents the system with the fan blade setting adjusted to achieve the required face flow of 18.88 m^3/s. Air leakage is not constrained, remaining at 30%. The fan supply flow is 26.97m^3/s. The system installation quality is not improved; an ‘installation quality factor’ of 30% is used.

Table 1. Operational features of three duct system cases.

Case	1	2	3
Face Flow	18.88 m^3/s	15.56 m^3/s	18.88 m^3/s
Leakage	20%	30%	30%
Fan Flow	23.6 m^3/s	22.23 m^3/s	26.97 m^3/s
Installation Quality	Good	Poor	Poor
Inlet Bell	Installed	No Bell	No Bell
Screen	95% Net Free Area	30% Net Free Area	30% Net Free Area
Silencers	Proper Connection	Non-Aerodynamic	Non-Aerodynamic
Friction Head Loss	Same Resistance	Same Resistance	Same Resistance
Coupling Losses	Same Resistance	Same Resistance	Same Resistance
Bend	Proper Installation	‘Kinked’	‘Kinked’
Duct Exit	Full Section	Reduced Section	Reduced Section

The contribution of each duct system component to power consumption and operating costs is presented in the following sections.

2.1 *Inlet bell*

The fan inlet bell ensures smooth air flow through the fan intake and serves to minimize entrance losses. Case 1 has a proper inlet bell installed and in Cases 2 and 3 the fan is installed without an inlet bell. Table 2 presents a summary of results for the 3 cases. For cases 2 and 3, substantial increases in operating cost of 723% and of 1,370% are noted when an inlet bell is not used. Table 2 clearly shows that, when an inlet bell is installed, significant energy and cost savings can be achieved.

Table 2. Head losses, power, and operating costs for inlet bell.

Case	Head Loss (Pa)	Power (kW)	Cost/Year ($/y)	% Change in Cost
1	14.73	0.59	412.28	-
2	108.90	4.84	3,393.06	723
3	160.27	8.64	6,058.39	1,370

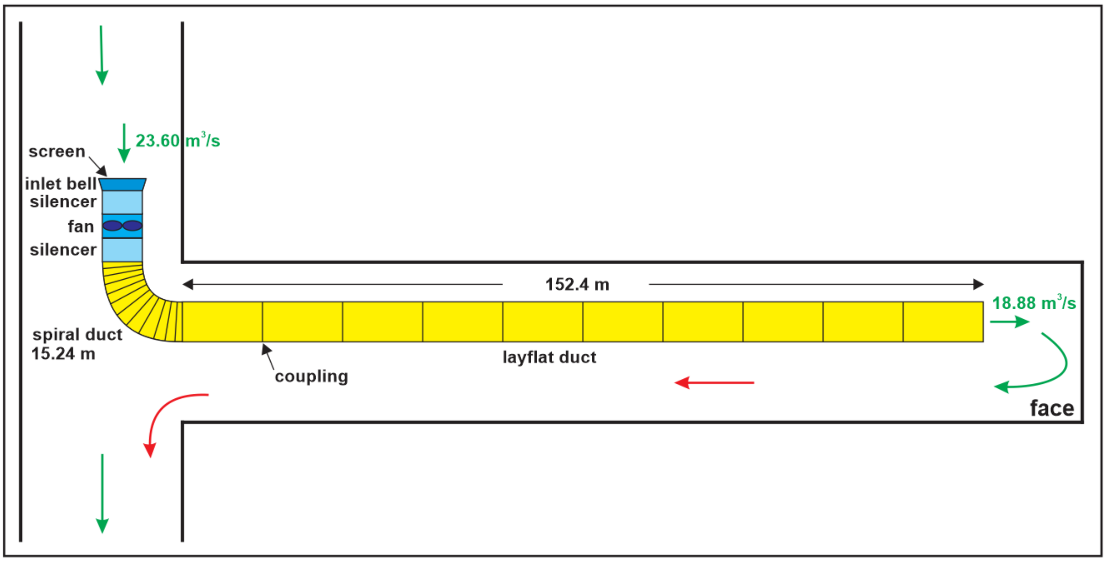

Figure 1. Auxiliary ventilation system configuration.

2.2 *Screen*

The fan screen prevents debris from entering the fan. Case 1 has a screen of 95% net free area installed and in Cases 2 and 3 the fan screen is partially blocked by the deposition of debris. Table 3 presents a summary of results for the 3 cases. For cases 2 and 3, substantial increases in operating cost of 340% and of 686% are noted when the screen is partly blocked with debris and not well maintained.

Table 3. Head losses, power, and operating costs for screen.

Case	Head Loss (Pa)	Power (kW)	Cost/Year ($/y)	% Change in Cost
1	11.29	0.45	315.99	-
2	44.65	1.99	1,391.19	340.26
3	65.71	3.54	2,483.91	686.06

2.3 *Silencers*

Silencers provide a level of noise reduction to meet specific needs and for compliancy with regulations. Case 1 has silencers properly connected to the fan and in Cases 2 and 3 the silencers have a non-aerodynamic connection to fan. Table 4 presents a summary of results for the 3 cases. For cases 2 and 3, relatively large increases in operating cost of 19.7% and of 45% are noted when the silencers are not properly installed.

Table 4. Head losses, power, and operating costs for silencers.

Case	Head Loss (Pa)	Power (kW)	Cost/Year ($/y)	% Change in Cost
1	49.77	1.99	1,392.95	-
2	53.50	2.39	1,666.93	19.67
3	53.50	2.89	2,022.36	45.19

2.4 *Friction head losses for layflat duct*

For the three cases, the layflat duct has the same frictional resistance, however the resistance pressures vary as a function of the airflow volumes passing through the duct column due to leakage effects. Table 5 presents a summary of results for the 3 cases. Because of the reduced flows, case 2 has a reduced operating cost of 19.1% and, for case 3, because of the increased fan flow, an increase in operating cost of 44.4% is noted.

Table 5. Head losses, power, and operating costs for layflat duct friction losses.

Case	Head Loss (Pa)	Power (kW)	Cost/Year ($/y)	% Change in Cost
1	604.66	21.60	15,136.12	-
2	469.54	17.47	12,240.01	-19.13
3	691.04	31.19	21,854.54	44.39

2.5 *Friction head losses for spiral duct*

For the three cases, the spiral duct has the frictional resistance, however the resistance pressures vary as a function of the fan flow. Table 6 presents a summary of results for the 3 cases. Because of the reduced fan flow, case 2 has a reduced operating cost of 1.2% and, for case 3, because of the increased fan flow, an increase in operating cost of 76.4% is noted.

Table 6. Head losses, power, and operating costs for spiral duct friction losses.

Case	Head Loss (Pa)	Power (kW)	Cost/Year ($/y)	% Change in Cost
1	226.75	9.06	6,346.37	-
2	201.23	8.95	6,269.83	-1.21
3	296.16	15.97	11,195.12	76.40

2.6 *Coupling losses for layflat duct*

For the three cases, the layflat duct has the same resistance due to couplings, however the resistance pressures vary as a function of the airflow volumes passing through the duct column due to leakage effects. Table 7 presents a summary of results for the 3 cases. Because of the reduced flows, case 2 has a reduced operating cost of 19.1% and, for case 3, because of the increased fan flow, an increase in operating cost of 44.4% is noted.

Table 7. Head losses, power, and operating costs for layflat duct coupling losses.

Case	Head Loss (Pa)	Power (kW)	Cost/Year ($/y)	% Change in Cost
1	64.27	2.30	1,608.96	-
2	49.91	1.86	1,301.10	-19.13
3	73.46	3.31	2,323.12	44.39

2.7 *Coupling losses for spiral duct*

For the three cases, the spiral duct has the same resistance due to couplings, however the resistance pressures vary as a function of the fan flow. Table 8 presents a summary of results for the 3 cases. Because of the reduced fan flows, case 2 has a reduced operating cost of 1.2% and, for case 3, because of the increased fan flow, an increase in operating cost of 76.4% is noted.

Table 8. Head losses, power, and operating costs for spiral duct coupling losses.

Case	Head Loss (Pa)	Power (kW)	Cost/Year ($/y)	% Change in Cost
1	71.42	2.85	1,998.86	-
2	63.38	2.82	1,974.75	-1.21
3	93.28	5.03	3,526.02	76.40

2.8 *Bend*

Case 1 has a properly designed bend and, in Cases 2 and 3, the installed bend is ‘kinked’, resulting in a higher resistance pressure. Table 9 presents a summary of results for the 3 cases. For cases 2 and 3, relatively large increases in operating cost of 97.6% and of 252.8% are noted when the bend is not properly installed.

Table 9. Head losses, power, and operating costs for bend losses.

Case	Head Loss (Pa)	Power (kW)	Cost/Year ($/y)	% Change in Cost
1	45.40	1.81	1,270.75	-
2	80.59	3.58	2,510.85	97.59
3	118.60	6.40	4,483.27	252.80

2.9 *Exit losses*

Case 1 has a properly installed duct end, with its full cross-section open, and in Cases 2 and 3 the installed duct end has its exit reduced in section, resulting in a higher resistance pressure. Table 10 presents a summary of results for the 3 cases. For cases 2 and 3, relatively large increases in operating cost of 109.2% and of 273.5% are noted when the duct end is not properly installed.

Table 10. Head losses, power, and operating costs for exit losses.

Case	Head Loss (Pa)	Power (kW)	Cost/Year ($/y)	% Change in Cost
1	157.07	5.02	3,516.58	-
2	337.29	10.50	7,356.40	109.19
3	496.41	18.74	13,134.63	273.51

2.10 *System component contribution summary*

Table 11 presents the contribution of each individual component, relative to Case 1, to annual operating costs. For case 2 the overall system component contribution to costs is 19.1% and for case 3 it reaches 109.6%. This clearly indicates the potential for cost savings when an auxiliary ventilation system is properly designed, commissioned, and maintained.

Table 11. Component percent contribution to annual operating costs.

Component	Percent $/year change relative to case 1	
	Case 2	Case 3
Inlet bell	723.0	1,369.5
Screen	340.3	686.1
Silencers	19.7	45.2
Friction layflat	-19.1	44.4
Friction spiral	-1.2	76.4
Joints layflat	-19.1	44.4
Joints spiral	-1.2	76.4
Bend	97.6	252.8
Exit	101.2	273.5
Overall	19.1	109.6

2.11 *Fan operation*

Figure 2 presents the fan curve and operating points for the 3 cases and Table 12 presents details of the fan operation. For cases 2 and 3, relatively large percent increases in fan input power and operating cost of 10% and of 94.5%, relative to case 1, are noted. It is pointed that, for case 2, the system is not in compliance since the face supplied flow does not meet regulatory requirements. Also, for case 3, the fan operates very close to stall. To reduce risk in both cases, the installed system components should be improved including, installing an inlet bell, maintaining the fan screen, correcting the silencer connections, installing a proper bend, and the correcting duct outlet. Also, the duct column installation quality should be improved, and air leakage controlled. These actions will bring the system operation close to the design specifications.

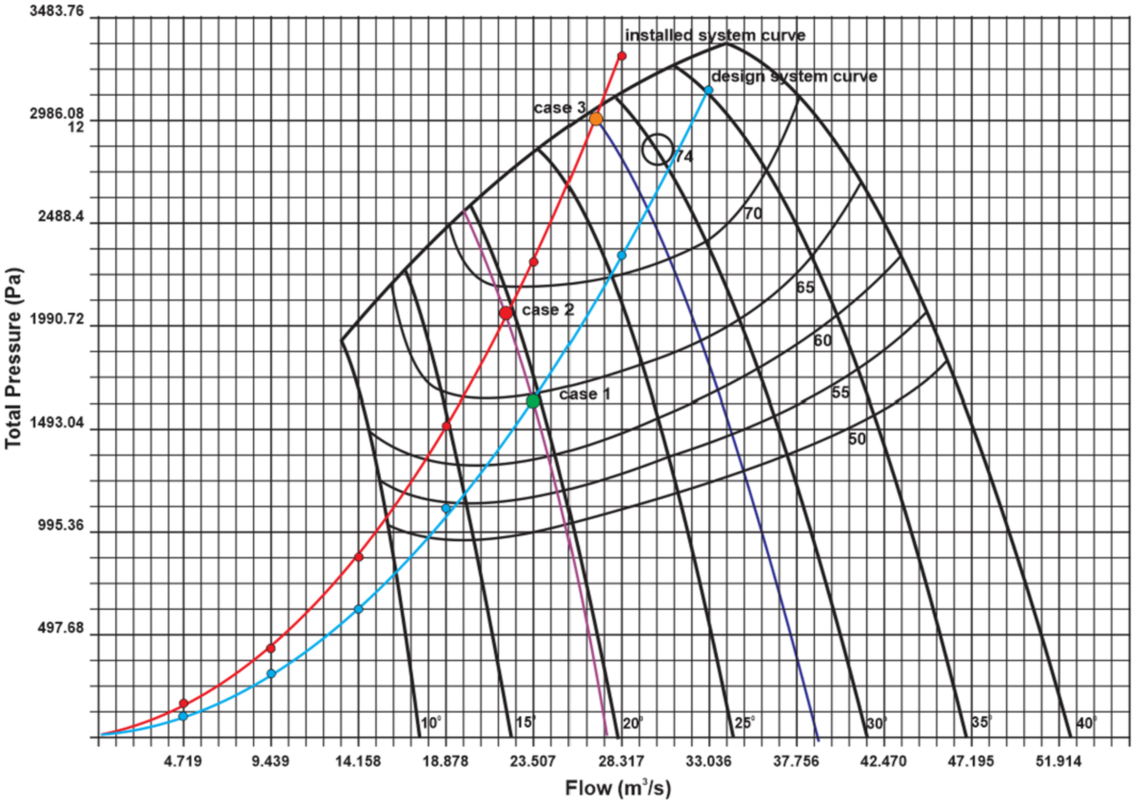

Figure 2. Fan characteristics and operating points for the three cases.

Table 12. Fan operation for the three cases.

Case	Flow (m^3/s)	TP (Pa)	Blade Angle (degrees)	Efficiency (%)	Brake Power (kW)	Input Power (kW)	Cost/Year ($/y)	% Increase in Cost
1	23.6	1,615.30	19.5	64.5	59.1	62.2	43,773	-
2	22.23	2,049.48	19.5	70	65.09	68.51	48,160	10
3	26.97	2,983.49	28	70	114.94	120.99	84,797	94.5

2.12 *Operational costs*

Table 13 presents annual fan operating costs as a function of the number of duct installations. Independent on the number of installations, fan operating costs increase by 10% and 93.7% for cases 2 and 3, relative to case 1. Typical hard rock mines may have well over 40 auxiliary ventilation systems installed to support development and production activities. For the case study presented, annual cost savings reaching some $1.65M can be realized when a system is installed and maintained according to design.

It is noted that the comparative analysis was based on direct costs only. It is recognized that ventilation training, asset management and preventive maintenance produce significant reductions in ventilation operating costs. While indirect costs are site dependent, the author has observed that when workers acquire practical ventilation training prior to working underground, which normally comes at a very nominal cost, considerable improvements in ventilation system performance are readily realized.

Table 13. Annual operating costs for multiple duct system installations.

Case	Number of Duct System Installations					
	1	5	10	20	30	40
1	43,773	218,865	437,730	875,460	1,313,190	1,750,920
2	48,160	240,800	481,600	963,200	1,444,800	1,926,400
3	84,797	422,983	847,965	1,695,930	2,543,895	3,391,860

3 CONCLUSIONS

This paper has demonstrated how the use of proper engineering design for optimal duct system installations would dramatically result in reduced energy consumption and in reduced operating costs. When properly designed, installed, and maintained, an auxiliary ventilation system can operate efficiently with substantial power and operating cost savings.

In a case study presented, it has been illustrated that savings in fan energy consumption exceeding 94% can be achieved by correctly commissioning and maintaining a properly designed auxiliary ventilation system.

4 REFERENCES

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