Evaluation of Savings from an Underground Fan Replacement Project

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***Abstract*— The savings calculation methodology from a fan replacement project is presented in this paper. The fans replaced are part of the underground ventilation system in a platinum mine. Initially, 290 axial flow fans rated at 45kW were to be replaced with carbon fibre composite fans. According to the manufacturer, the carbon fibre construction allowed for an optimum blade shape which results in the carbon fibre fan being more energy efficient. However, after the first few fans were replaced, it was discovered that the mine's blasting activities caused the carbon fibre fans to crack and eventually fail. Fortunately, the manufacturer was able to produce a steel fan with similar performance to that of the carbon composite fans and continue replacing old fans in the mine. The savings were independently verified according to the International Performance Measurement & Verification Protocol (IPMVP). This involved testing old and new fans in a BS848 test duct and comparing the old and new fans at various operating points on their fan curves and making adjustments for operating conditions such as air density underground vs at the test duct. It was found that the new fans saved 5kW on average, across a range of operating points.**

***Index Terms*—Measurement and Verification, energy efficiency, underground ventilation, composite fans, axial flow fans, demand side management.**

I. INTRODUCTION

The South African electricity utility, Eskom, has been operating a large demand side management (DSM) programme where companies receive a subsidy for implementing load management or energy efficiency projects. This programme is largely funded by rate payers through a DSM levy applied to the electricity tariff. All of these projects are independently audited by different teams based at universities around the country. This independent assessment ensures the integrity of the DSM programme and protects the energy management industry and rate payers from poor performers since the subsidy is dependent on the savings achieved. The assessment of the energy savings from the DSM programme is done according to a local standard [1] which is based on the International Performance Measurement & Verification Protocol (IPMVP) [2] and is known as Measurement & Verification (M&V). The IPMVP and other similar protocols [3-5] advocate the calculation of savings using adjustments for changes in operating conditions between the old and new systems. The adjustments are calculated based on a model of the old system operating under the conditions of the new system [1, 6]. This allows one to calculate the savings according to a set of actual or chosen reference operating conditions.

This particular project, which we M&V'd, involved the replacement of 290 axial flow, 45kW, 750mm diameter fans which were part of an underground ventilation system in a platinum mine. The new fans were initially made of carbon fibre however they were found to be prone to cracking during blasting underground. Eventually the manufacturer was able to produce a steel fan with similar performance and continue the project. The old and new fan curves are presented below in Fig. 1.

II. UNDERGROUND VENTILATION SYSTEM OPERATION

Underground ventilation systems are typically run 24 hours a day and are closely monitored by a ventilation department to ensure the safety of the miners underground.

Numerous fans both above and below ground may form part of the system, extracting air out of or forcing air into the mine. The particular fans of this project were used underground in ducts of 750mm diameter which are continuously lengthened or moved as new areas of the mine are developed. Thus most fans are likely to operate under a range of conditions throughout their operating lives. A small number of fans may operate in relatively static configurations though.

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It should also be borne in mind that air density changes continually depending on atmospheric conditions in the mine but that it generally increases with depth.

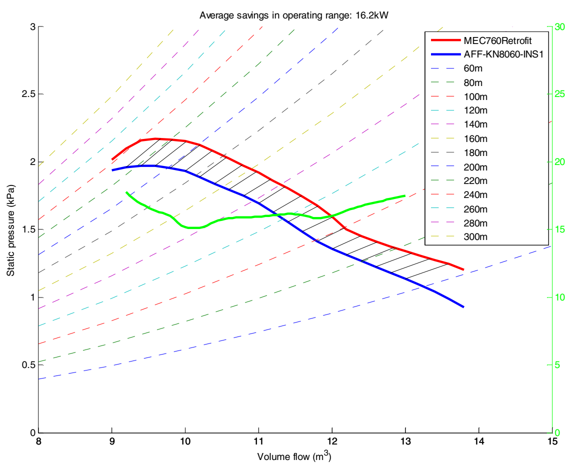

Figure 1. New and old fan curves and expected saving

III. M&V Methodology

The main goal of the project is to reduce energy consumption while maintaining output delivery. To compensate for the potential placement of a new fan in a different operating environment all potential operating points need to be considered.

To determine the operating point of a fan on its performance curve it is necessary to measure:

- Volumetric flow (m^3/s)
- Static pressure (kPA)
- Air density (kg/m^3)
- Rotational speed (rpm)
- Electrical power (kW)

One option is to take measurements on the fans during swap out, confirming that the new fans deliver the same or higher flow with lower power consumption. However, taking numerous measurements underground is time consuming and only a sample of fans could feasibly be measured by the M&V Team. Additionally, if adjustments are to be done based on different duty points then the fan curves of both fans would also be required.

Due to the difficult and constantly changing conditions underground and the number of measurements required it was decided that the old and new fans should be tested above ground in a standard duct.

Based on recommendations from the mine ventilation engineers, the savings would then be calculated at volume flow rates ranging from 9.5-13m^3/s and an air density of 1.2 kg/m^3. This was deemed to be representative of the operating conditions of the fans.

A. General Methodology

Savings are calculated based on comparison of the averaged power consumption of a sample of old versus new fans. This is conducted by comparison of averaged fan performance curves obtained by a calibrated BS848 test [7]. These tests are to be conducted above ground for both the new and old fans. The curves are adjusted to the reference conditions chosen by the mine.

A comparison will be made between the sample of old fans operating over a range of flow rates (e.g. 9.5m^3/s – 13m^3/s) and a new fan over the same range. Power savings are then calculated by adjusting the new fan to the old fan's operating point by using the appropriate fan laws [8] and the measured fan curves obtained for the agreed upon sample size. This adjustment is required to compare the fan performances at the same operating point.

The fan manufacturer supplied the BS848 test duct and the mine personnel were responsible for performing the fan tests on a sample of old and new fans. The M&V Team occasionally witnessed the fan tests and took its own measurements on the test duct to verify the fan curves.

Some of the old fans, removed from the mine, were in unacceptable condition with blades missing or other major damage. Therefore, it was decided that the new fans should be compared to a sample of refurbished old fans.

B. Detailed Fan Comparison Technique

1) Acquire fan performance curves i.e. power and static pressure versus air volume flow rate at the reference conditions chosen by the mine for the new and old fan. (If the curves are supplied at different atmospheric conditions then adjust them using the fan laws.)

2) To allow for more simple arithmetic, the curves are mathematically described by individually fitting each of the curves discrete data points to a second order polynomial using a least squares method:

$$P_{new} = a_1 + a_2 q + a_3 q^2 \quad (1)$$

$$P_{old} = a_4 + a_5 q + a_6 q^2 \quad (2)$$

$$W_{new} = a_7 + a_8 q + a_9 q^2 \quad (3)$$

$$W_{old} = a_{10} + a_{11} q + a_{12} q^2 \quad (4)$$

A second order polynomial was found to adequately describe the fan curves. A third order polynomial could be used to improve the accuracy of the fit if extended volume flow ranges are of interest or if a quadratic fit is not sufficiently accurate. (R^2 values of >0.9 are recommended.)

3) The savings are to be evaluated over a predetermined range of flow rates. This implies evaluating the savings over said range at predetermined increments. The old fan curve (P_{old}) is therefore calculated with $q_1, q_2, .. q_n$ values of q e.g. 9.5m^3/s, 10m^3/s, … ,12m^3/s, giving various values of static pressure (P) for the old fan:

$$\mathrm{P}_n = a_4 + a_5\, q_n + a_6\, {q_n}^2 \qquad (5)$$

4) Assume a system resistance curve described by:

$$P_{duct\,n} = k_n\, {q_n}^2 \qquad (6)$$

5) Calculate k_n for a selected increment (P_n, q_n) on the “old fan” curve.

6) Using equations 1 and 6 simultaneously ($P_{duct\,n} = P_{new}$), solve for the volume flow rate at the current duct resistance for the new fan, q_{new_n}.

7) Calculate the power consumption for the new fan, W_{new_n}, for this flow rate using equation 3.

8) Adjust this power consumption for the new fan to the operating (volume flow rate q_n) point of the old fan by utilizing the appropriate fan law (power is proportional to the ratio of flow rates cubed):

$$W_{new\;n}^{adjusted} = \left(\frac{q_n}{q_{new_n}}\right)^3 \times W_{new_n} \qquad (7)$$

9) Calculate the adjusted savings for the current increment:

$$\mathrm{Savings}_n = W_{old_n} - W_{new\;n}^{adjusted} \qquad (8)$$

10) Percentage saving for increment n is then:

$$\%Savings_n = \frac{Savings_n}{W_{old_n}} \times 100 \qquad (9)$$

11) Repeat steps 5 to 10 for all increments over the volume flow range under consideration.

12) Calculate an overall average saving over the volume flow range under consideration. An equidistant set of increments (e.g. in steps of 0.5 m^3/s) therefore implies an equal weighting across the range.

Selected steps are illustrated graphically in Fig. 2. Note that the new fan may not necessarily have lower flow rates than the old fan.

In this case study, the savings were given relative to what the new fans would have consumed had they been operated, by whatever means, to match the performance of the old fans. Instead of adjusting the new fan to the old fan’s operating point, the adjustment could be done the other way around. Alternatively, the higher performing fan could always be adjusted to the lower performing fans operating point or vice versa, depending on what perspective the stakeholders prefer.

In summary, once the fan curves have been obtained, an operating point must be chosen on one of the pressure vs flow curves. A system resistance curve is then drawn through that operating point, say (P_{old} , q_{old}). The duct resistance curve is used to determine what the pressure and flow of the new fan would be in that duct (P_{new}, q_{new}). The new fan power can be found by looking up/calculating W_{new} at q_{new}. The new fan power is then adjusted by the cubed ratio of q_{old} to q_{new}. The savings are then the difference between the old fan power and the adjusted new fan power. This process is then repeated at n points in the volume flow range of interest.

The test duct is photographed in Fig. 3 below.

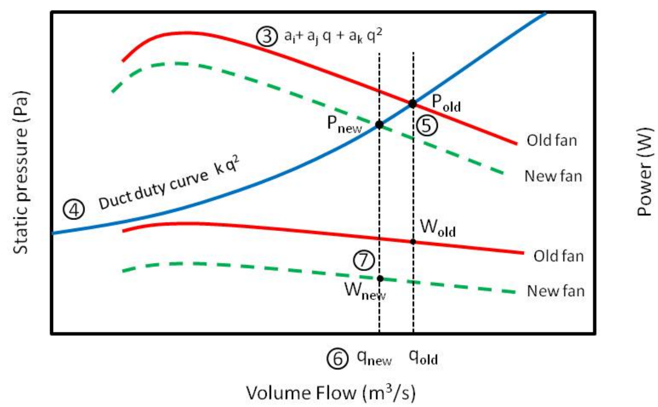

Figure 2. Illustration of selected steps to determine the saving

Figure 3. BS848 fan test duct

C. Notes on volume flow measurement

The flow measurement should be done according to the Log-Tchebycheff (or similar) method [9] because the air velocity varies across the duct. Various possible air velocity profiles are possible. Velocity is lowest near the sides of the duct and higher towards the centre, however the velocity may be higher on one side of the duct than the other. Therefore, several dynamic pressure measurements, using a manometer and pitot tube, should be made at pre-defined points around the duct. Fig. 4 below shows the differential pressure or air velocity measurement points as a function of diameter for the Log-Tchebycheff method.

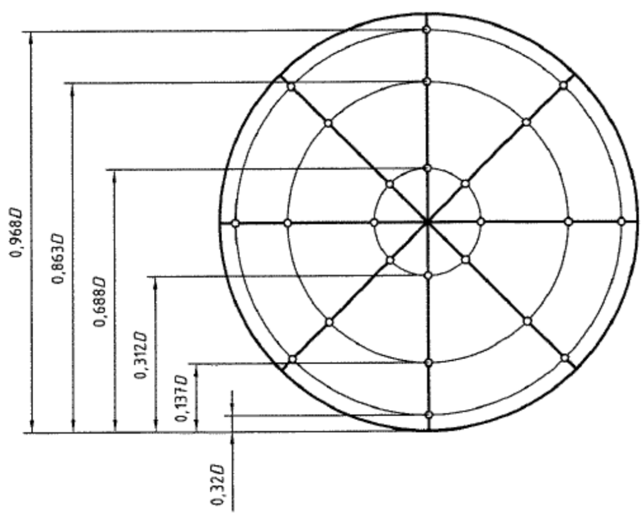

Figure 4. Siting of measurement points in a circular section according to the Log-Tchebycheff method

IV. M&V RESULTS

Figs. 5-6 show the average of the old fan curves and a new fan curve. Fig.7 shows the percentage saving at different flow rates depending on whether the new fan is adjusted to the old fan operating point or vice versa.

Using the first adjustment method the saving varies from 3.6kW to 7kW per fan with an average of 5.4kW across the flow rate range. Using the second adjustment method the saving varies from 1.6kW to 8.5kW per fan with an average of 5.2kW.

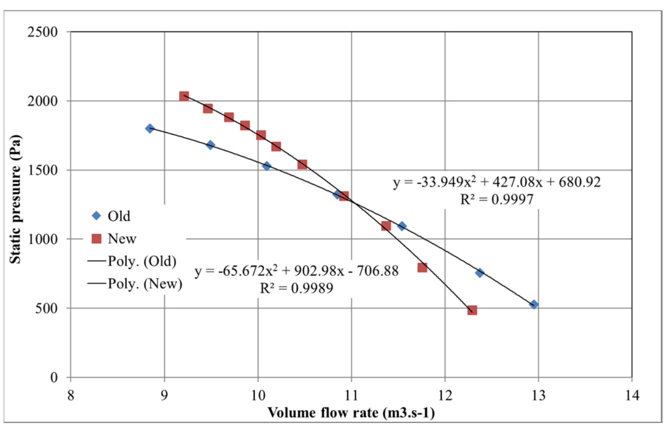

Figure 5. Average old and new fan pressure vs flow characteristic

Fig. 8 shows the old and new fan efficiencies across the flow range. The new fans are more efficient at higher system resistances but the new fan efficiency falls below that of the old fans at higher flow rates. While the new fan delivers less flow at lower system resistances, its power consumption is lower than that of the old fans resulting in a power reduction despite its lower efficiency.

The old fan curves exhibited some variance from one another but the uncertainty in the savings was relatively low with a precision of 14.8% at the 95% confidence level.

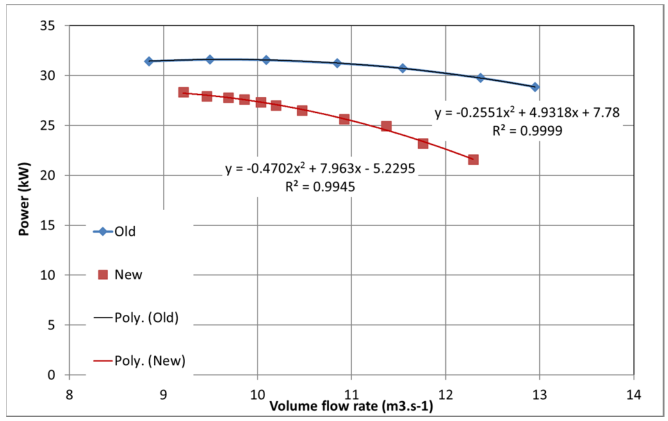

Figure 6. Average old and new fan power vs flow characteristic

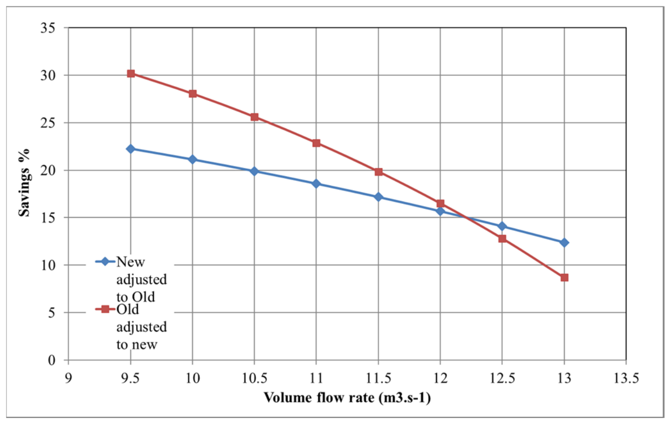

Figure 7. % Power saving vs flow depending on which adjustment methodology is used.

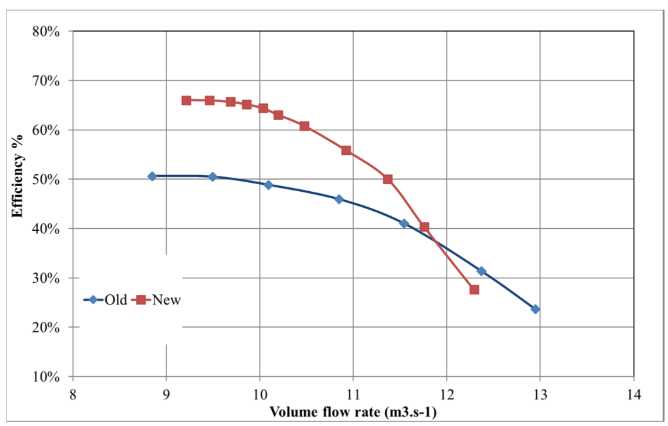

Figure 8. Old and new fan efficiency characteristic

V. Conclusions

A methodology for comparing fans based on third party verification of their performance curves, obtained from a standard test duct, has been presented. The methodology involves using the fan laws to adjust the operating powers of the fans to determine what their power consumption would be if they were providing the same flow at a number of different theoretical duct resistances.

This methodology is useful when:

- in situ testing is not feasible, possibly due to cost, safety concerns or a concern over lack of measurement accuracy
- a standard test duct is available
- the fans must be compared across a range of system resistances
- the stakeholders are willing to accept results reported relative to reference or normalised conditions
- savings must be determined from a sample of a larger population.

For fan replacements where the system resistance is fixed, in situ spot measurements would likely be a cheaper solution to determine the savings. For a constant speed application, one could verify whether the new fan provides better flow and if so simply subtract the new fan power from that of the old.

For variable speed applications or when an adjusted savings calculation is preferred by the stakeholders, then the fan curves will need to be determined and could be combined with in situ measurements to determine the energy savings using similar methods to those used here.

Acknowledgment

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