

Fan Total Pressure or Fan Static Pressure: Which is correct when solving ventilation problems?

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Introduction

All ventilation practitioners need to be able to select suitably sized airways, or suitably sized fans, for a variety of mine applications. Today, this can be achieved rapidly by the use of PC-based network simulation packages.

However, a review of the literature and of the ventilation simulation programmes currently available indicates that there is disagreement as to whether to use fan total pressure (FTP) or fan static pressure (FSP) when solving a network problem.

In addition, some ventilation courses and reference books teach students that fan solutions should be in terms of FTP and others in terms of FSP. Others, perhaps even more frustratingly, are silent on the issue, referring merely to the anonymous term "fan pressure".

This disagreement is leading to confusion and, frequently, incorrect solutions to ventilation problems.

A clear review and understanding of the issues is therefore highly desirable. This will result in less errors and a more consistent approach with more reproducible results.

Discussion

Frictional Pressure Drops

It can be demonstrated from Bernoulli's equation,¹ that at any point within a steady airflow, there is a *static* (or bursting) pressure that acts equally in all directions. There is also a *velocity* (or stagnation) pressure, which has its maximum value in the direction of the airflow. The algebraic sum of these two pressures is called the total pressure at that point. Velocity pressure is always positive, but static pressure (which is usually measured as gauge, rather than absolute pressure) can be either positive or negative.

In a steady airflow, and in the absence of frictional pressure or shock losses, static pressure and velocity pressure are interchangeable.¹ For example, as air moves through a tunnel of decreasing cross sectional area, the velocity (and hence velocity pressure) will increase, and the static pressure will reduce commensurately so that the total pressure remains constant. It is important to realise that in a frictionless system, only the total pressure remains constant; the

static and velocity pressure will vary according to the airway size at any point.

Any ventilation simulation requires solution of Kirchoff's 1st and 2nd laws, as applied to fluid networks.⁶

Kirchoff's 1st law states that the mass flow of air entering any junction in a network must equal the mass flow of air leaving the junction. In practice, as the density of air entering and leaving any particular junction can be considered to be constant, Kirchoff's 1st law effectively states that:

$$\sum_{i=1}^n Q_i = 0, \quad (1)$$

where n is the number of airflows into and out of a particular junction

Kirchoff's 2nd law states that the sum of all frictional pressure drops around any closed loop (a "mesh") in a network must be zero, after accounting for the effects of fans and natural ventilation pressure.⁶ In other words:

$$\sum (p - p_f) - NVP = 0, \quad (2)$$

where p are fan pressures in the loop, and p_f are frictional pressure drops around the loop

It is convenient for the remainder of this discussion to ignore NVP, which is usually done in non-thermodynamic network simulation programs without introducing significant error, leading to the expression:

$$\sum (p - p_f) = 0 \quad (3)$$

It was noted earlier that static pressure and velocity pressure would increase or decrease with changes in cross-sectional area of the airway, even in the absence of friction. Only the total pressure would remain constant. Therefore, any frictional pressure drop in an airway, (which includes shock losses, which are merely a particular type of frictional pressure loss), will be at the expense of total pressure. Only when the airways are of constant cross-section (in which case there will be no change in velocity pressure along the airway) will the frictional pressure drop also be equal to the drop in static pressure along the airway. The pressure term in equation 3 must therefore be total pressure. Any program that assumes that frictional pressure loss is equal to a loss in static pressure will only be valid for the unusual case in

which the airways throughout the mine are of constant cross-sectional area.

Let us now consider the issue of fan pressures.

Fan Total and Fan Static Pressures

There is a general consensus regarding the definitions of the terms FTP and FSP, including agreement between authorities such as British Standards² and ASHRAE.⁴ However, there are some notable exceptions.⁷

ASHRAE defines FTP as the total pressure at the fan discharge (TP_o) minus the total pressure at the fan inlet (TP_i). The fan velocity pressure (FVP) is defined as the pressure corresponding to the bulk air velocity and air density at the fan discharge (VP_o).

The FSP is then defined as the difference between the FTP and the FVP.

The application of these concepts to the full range of fan configurations is found in Jorgensen⁵ (a particularly excellent reference) and ASHRAE.³ These discussions are comprehensive and are not repeated here; they should be reviewed if any confusion remains in the reader's mind. However, some important points are relevant to the subsequent arguments:

Firstly, the FSP is *not* the increase in static pressure across the fan. FSP is defined only in terms of FTP and FVP; unlike FTP and FVP, FSP has *no* physical significance of its own. In effect, FSP is the difference between the average static pressure at the fan outlet (SP_o) and the average total pressure at the fan inlet (TP_i).

Secondly, FSP is *not* generally the static pressure on the "inbye" side of the fan.

Thirdly, inlet losses occur as the air enters the fan and are charged to the fan curve. Outlet losses for a fan discharging to atmosphere are equal to one velocity pressure (i.e. one FVP). Where a fan discharges into a tunnel, the outlet losses are less than one FVP as the air remains constrained inside the tunnel and therefore some (or all) of the velocity pressure is available as useful total pressure. An estimate of the actual loss can be calculated by treating the fan discharge as a sudden expansion. The usual formula⁶ is:

$$X_{\text{discharge}} = (1 - A_{\text{outlet}}/A_{\text{tunnel}})^2 \quad (4)$$

Where

$X_{\text{discharge}}$ is the shock loss (in FVP) at the fan discharge,

A_{outlet} is the cross-sectional area of the fan outlet

A_{tunnel} is the cross-sectional area of the tunnel at the fan discharge.

In practice, $X_{\text{discharge}}$ can range from almost nil to a full FVP.

By convention, these outlet losses are not charged to the fan curve. This is because, traditionally, the velocity pressure at the fan outlet was considered to be entirely "useless" or "wasted

energy, and therefore ignored. This is certainly true of fans discharging to atmosphere, but is not true of fans discharging into a tunnel or shaft. This concept of wasted pressure can be seen in older texts such as MacFarlane,⁹ which at times use the terms "Total W.G." and "Useful W.G" for fan total and static pressure respectively (where W.G. is water gauge, i.e. a measure of pressure).

For a large modern mine that may have dozens or even hundreds of main and circuit fans (excluding auxiliary fans used only for ventilating development ends), the only truly "wasted" velocity pressure therefore of that which exhausts to atmosphere, along with some portion of the FVP for the other fans in the mine.

Another way of looking at this is to consider a tunnel which forms a totally enclosed loop, and which has a fan in it to move the air around the loop. Assume the fan discharge occupies the full tunnel area. Once the air has initially been accelerated to its steady-state velocity, all the fan pressure (i.e. the fan total pressure) is available to overcome the frictional pressure drop around the loop. If it is assumed that the driving force is only the fan static pressure, then what happens to the residual fan velocity pressure? It is also clear from this example, that solving this simple network using FTP and FSP cannot both be correct.

In practice, fan discharges do not occupy the full tunnel area. Therefore neither FSP nor FTP will be entirely accurate. FSP is an underestimation of the pressure available to overcome mine resistance, and FTP is an overestimation of the pressure available to overcome mine resistance.

It should also be noted that purpose-built surface intake fans usually have fan curves referenced to the top of the shaft collar. This will take into account friction losses in the fan pieces and bends between the fan and the collar and any shock losses to the point of the shaft collar. Therefore, main intake fans are an example where the entire FTP is available to overcome mine resistance.

It has been shown above that ventilation networks must be solved in terms of total pressure. Continuing from this premise, let us assume that an underground fan is discharging into a tunnel of the same cross-sectional area as the fan discharge. This is an artificial situation, but will serve to illustrate the most extreme consequences of using FSP as against FTP. We will then return to a more typical installation.

Implications of using FSP instead of FTP for ventilation planning

There are numerous consequences when static pressure is used for ventilation planning, rather than total pressure. Some of these include:

Over specification on fans

Figure 1 shows the frictional pressure drop in

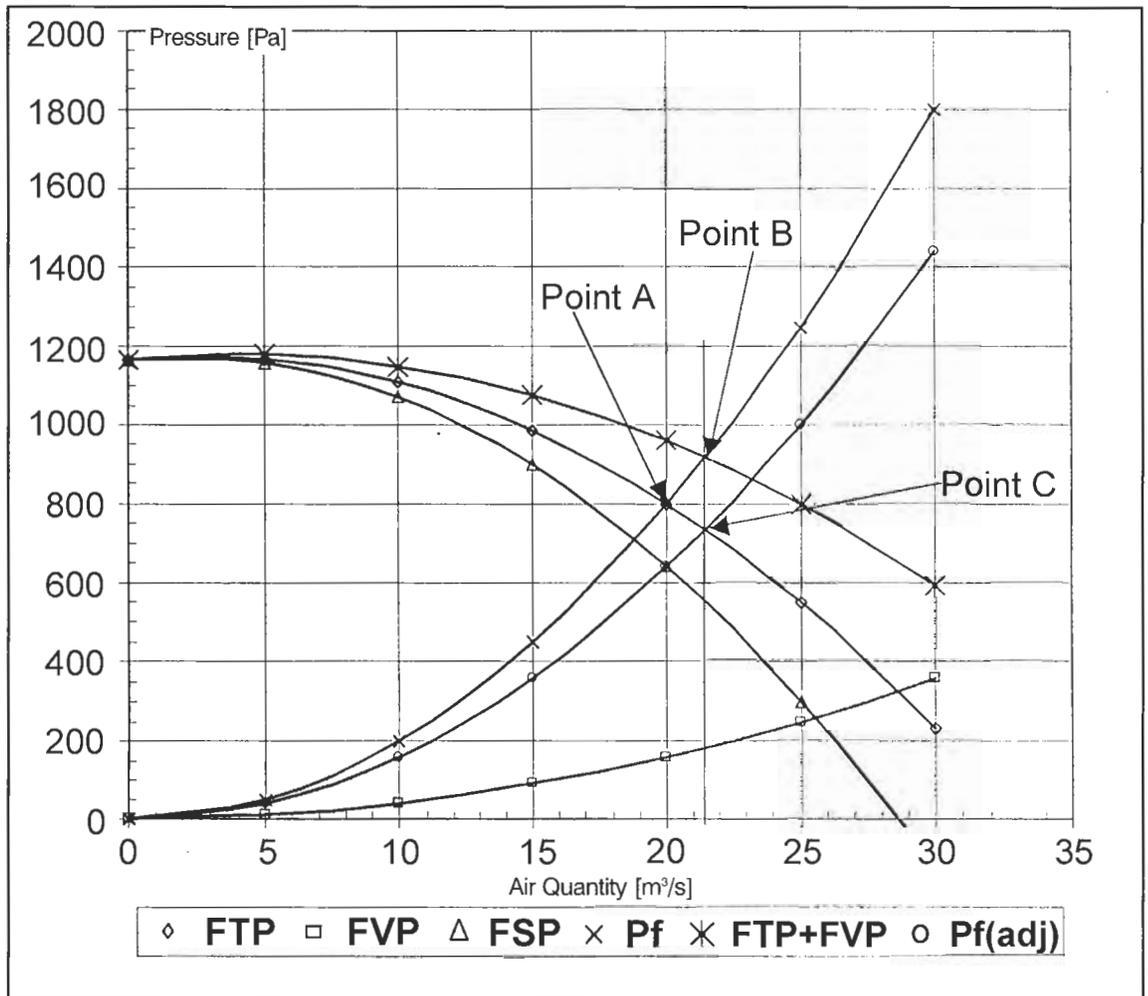


Figure 1. Pressure versus airflow for an in-line fan, illustrating problems when assuming airway resistance is overcome using FSP, rather than FTP. P_f is the true airway resistance. Point A is the fan pressure required to produce $20 \text{ m}^3/\text{s}$. This is on the FTP curve, which results in the FSP curve as shown (below the FTP curve). However, if this curve is mistakenly taken to be the fan FSP curve, then the FTP associated with such a fan is on the FTP+FVP curve, which results in a new solution ($21.4 \text{ m}^3/\text{s}$) at point B. If it is believed that this point is on the original fan curve, then this can only be so if the operating point is at point C. In turn, this can only occur if the airway resistance is $P_f(\text{adj})$.

an airway with a resistance of $1 \text{ N s}^2 \cdot \text{m}^{-8}$. Also shown is the fan curve (the fan being a main intake fan, or an underground fan with its dis-

charge occupying the entire tunnel). The fan's FTP, FSP and FVP shown separately. Clearly, for any value of Q on the curve, $\text{FTP} = \text{FSP} + \text{FVP}$.

The correct operating point (point A) for the fan is $20 \text{ m}^3/\text{s}$ at which point the fan total pressure is 800 Pa . The FSP at this point is 641 Pa .

Assume a simulation package is used in which the frictional pressure drop (signified by the mine resistance curve, P_f in figure 1) is met by the fan static pressure. In this case, the program will find that the operating point is $20 \text{ m}^3/\text{s}$ at a FSP of 800 Pa (point A), at which point the FTP is 959 Pa . The "solutions" are the same, but the fan being selected is different; one has a FSP of 641 Pa and the other a FSP of 800 Pa . If this operating point is taken to a fan manufacturer, it will result in different fans being purchased.

In general, simulations that use FSP instead of FTP will overestimate the pressure requirement of the fan.

Increased airflow

Let us assume that the ventilation officer has

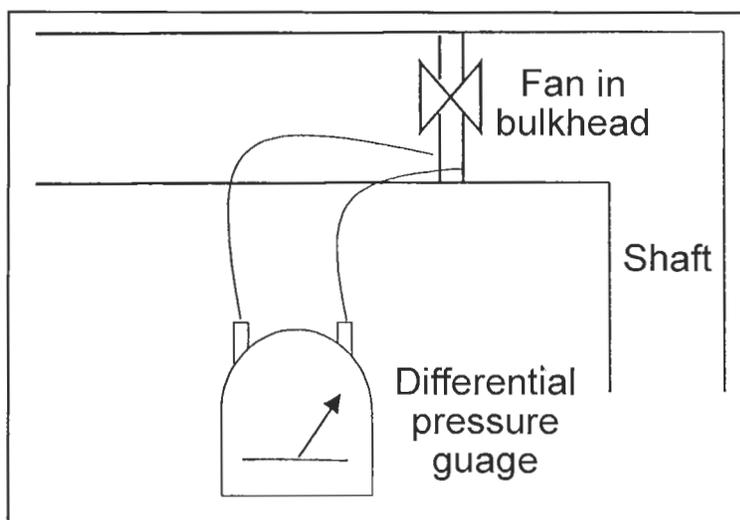


Figure 2. Measurement of differential pressure across bulkhead containing fan results in FTP less shock losses at the fan outlet, not FSP, providing tubes are in quiescent area on each side of wall.

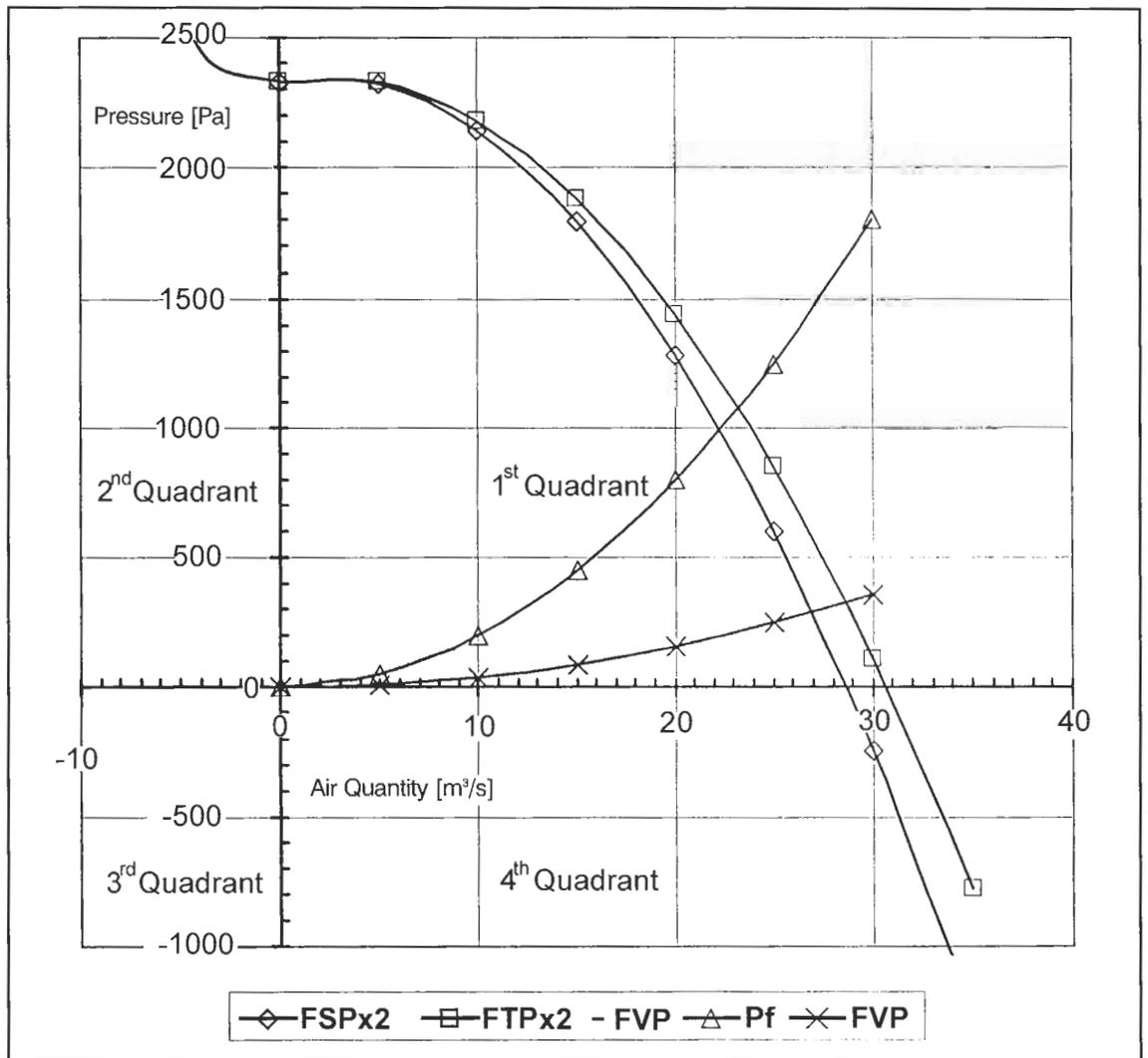


Figure 3. Pressure versus airflow, showing problems when using FSP curve to construct a combined fan curve for two fans in series. Note that the curve which is double the single fan FSP curve ($FSP \times 2$) is not equivalent to the curve which is double the single fan FTP curve less one FVP ($FTP \times 2 - FVP$). The solutions will not produce the same operating point irrespective of the actual mine resistance.

selected a fan based on FSP and the fan has been purchased and installed. The mine operating point will be at point B in Figure 1. The actual airflow through the airway will be 21.4 m³/s, rather than the value shown in the model of 20 m³/s. In this case, the additional airflow is modest (10%); however, if the fan had a flat performance curve, the additional airflow could be quite significant.

Increased capital and operating cost

The higher-pressure fan selected on the basis of FSP will cost more to purchase than is actually required. Furthermore, to reduce the airflow to the required amount, pressure will need to be destroyed in a regulator, or the fan may need to be adjusted, which usually results in lower fan or system efficiencies. The alternative is to operate with the higher airflow. However, as fan power is proportional to the cube of airflow, all these solutions add unnecessary capital and operating costs, especially when escalated over the fan life.

Incorrect volume surveys

Few mines today measure airway resistance

values, except perhaps in the more critical vertical airways, where barometric pressure surveys are relatively quick and accurate. Most operations simply look up a set of friction factor tables, construct a model, and then conduct a volume survey to "adjust" the friction factors in the model, including shock losses. Therefore, consider the same fan installation as in Figure 1. The fan based on FSP has now been purchased and installed. A volume survey is then conducted and the actual airflow will be measured at 21.4 m³/s. The ventilation officer examines the fan curve (FSP) and finds that at this flow, the fan must be operating at point C (21.4 m³/s), rather than point A (20 m³/s) as he has high confidence in his volume data. He knows that the only way this can occur is if the friction ("K") factor of the airway is lower than the true value that he has put into his model. He then "back calculates" a K factor that will be about 25% lower than the true value. This is then perpetrated through the ventilation model.

Incorrect pressure surveys

On the rare occasions where trailing tube (or

other) pressure differential surveys are conducted, the concept that frictional pressure loss is a function of changes in static pressure only leads to the erroneous practice of only measuring static rather than total pressure, and then using differences in static pressure to calculate airway resistances. Frequently the individual errors involved in this will be small, but the cumulative errors can be large and can be inconsistent.

Incorrect fan surveys

The assumption that FSP is the only driving force that offsets the mine friction and shock losses also results in other problems when assessing fan performance.

Consider figure 2. This is a typical circuit fan installed in a ventilation bulkhead or stopping at the top of a raise. The ventilation officer has no access to side of the fan against the raise, but uses a pressure gauge and a short length of plastic hose through the wall to measure the (static) pressure across the bulkhead. He then assumes that this is the FSP, because his simulation program works in FSP. However, this pressure is not FSP; it is the FTP less some allowance for shock losses at the fan discharge. This can be understood by noting that the definition of FTP is the increase in total pressure across the fan. For a fan in a bulkhead, there is no velocity pressure in the still (quiescent) air immediately on either side of the bulkhead outside the influence of turbulence at the inlet or outlet of the fan; therefore the difference in these values is the FTP less the discharge loss. This discharge loss could range from 0 to 1 FVP, which in turn could be anything from 0 to 1500 Pa. This could result in a considerable error.

In this example, if the ventilation officer measured both the "fan pressure" (i.e. the pressure across the bulkhead) and the airflow through the fan, he would find that the resulting point did not plot on the fan curve. As this is a physical impossibility, he may (wrongly) suspect that the fan is not performing to specification, or that the fan blade angle is incorrect, etc.

Incorrect solutions with multiple fans

When two fans are connected in series, the FTP for the combined fan is equal to the sum of the FTP of each individual fan (ignoring compressibility effects). However, the FSP for the combined fan is not equal to the sum of the FSP values for each fan, because air at the same velocity passes through each fan; therefore the FVP for the combined installation is the velocity pressure of the air exiting the second fan. Figure 3 shows the same fan and mine resistance as for figure 1, but for two fans in series. It can clearly be seen that the FSP curve calculated by deducting the FVP from the combined FTP curve ($2 \times \text{FTP} - \text{FVP}$) is quite different from a FSP curve calculating by doubling each individual fan's FSP ($2 \times \text{FSP}$).

The free-delivery zone

It is seen from figure 1 that the FTP curve can be positive, even when the FSP has fallen to zero. In this region, the resistance on the fan has fallen to such a low value that the fan is in "free-delivery". In fact, it is quite possible for fans to actually operate in the "4th quadrant" (a reference to operating at positive airflow and negative pressure). This occurs when the resistance on the fan actually becomes negative (typically assisted by some other fan in series with it). In this case, the fan produces even more airflow than its 1st quadrant fan curve shows. Somewhere in the 4th quadrant, the airflow reaches a maximum (the "choke point") and further reductions in pressure across the fan only result in reduced airflow. "Unequally yoked" fans in series may deliberately or inadvertently operate in this zone; it would be rare for a ventilation officer to purposely select a fan to operate in this region. However, using FTP rather than FSP curves will provide more accurate simulation results when a fan is in or near this zone, particularly when two or more unequal fans are linked in series.

Incorrect assumptions about the role of fan inlet and outlet pieces

The role of the fan inlet is to direct the air into the fan casing with minimum entry shock losses. These shock losses are charged to the fan curve. Inlet cones or bellmouths are therefore equally important irrespective of whether a fan is intake, exhaust, or in-line.

However, the role of the fan outlet piece is to two-fold: to reduce shock losses on exit and also to recover some of the velocity pressure that would otherwise be wasted. Both these reasons are valid for fans discharging to the atmosphere. However, for fans discharging into a duct (e.g. a blowing or in-line fan), the fan velocity pressure is not entirely wasted. Therefore the role of the outlet piece is only to reduce shock losses at the exit. These losses are typically smaller than the velocity pressure at the outlet; therefore the importance of an *evasé* for fans blowing into a mine, or installed as circuit fans within the mine, is generally less than for fans exhausting to atmosphere. However, a misunderstanding of the role of FSP can lead to ventilation officers installing *evasés* with very good pressure recovery factors as underground fans, based on cost analyses that assume that all the velocity pressure not recovered in the *evasé* is wasted. This is incorrect and can lead to unnecessary size and expense in the *evasé* itself, including mounting costs, and even the expense of increasing the size of the underground excavation to install such the *evasé*.

Problems in using FTP

Loss of conservatism

Some practitioners may argue that using FSP rather than FTP provides an element of conser-

vatism in the final fan (or airway) selection. However, it is important to note that this “conservatism” may range from nothing (in the case of a mine with exhaust fans mounted at the outlet of all exhaust airways, and no other fans in the system) to an unpredictably large amount for a mine with all underground fans in similar sized tunnels, and large diameter airways exhausting to atmosphere. This may result in excessive conservatism. It would be preferable to explicitly allow for “conservatism” in the design, after taking into account the costs and the benefits weighted according to each estimation risk (e.g. the treatment of a risk that more airflow might be required due to more diesel equipment being used may require different engineering judgement as to where some “fat” will be built into the system, than the risk of having higher friction factors than predicted).

Conclusions and recommendations

Frictional pressure losses in an airway are always at the expense of total pressure, and only in unusual circumstances, would these be equal to the loss in static pressure. Network simulation models should therefore work in total pressures, not static pressures.

Neither FTP nor FSP curves are technically correct for ventilation simulations. For fans exhausting directly to atmosphere, FSP curves are correct. However, for blowing or in-line fans, FSP curves will underestimate the available pressure for overcoming mine resistance, and FTP curves will overestimate the available pressure.

The necessary shock loss corrections to FTP curves (or FSP curves) can easily be calculated based on the fan outlet diameter and the tunnel cross-sectional area in which the fan is mounted.

The necessary allowance for velocity pressure exit losses from the mine should be made by deducting one airway velocity pressure at the exit of each exhaust airway into atmosphere or, for fans discharging directly to atmosphere, the discharge fan velocity pressure. Where an easé (without a fan) is at the discharge of the airway, the shock loss should be commensurately less than a full velocity pressure.

Alternately, the fan curve for those fans exhausting to atmosphere can be recalculated so as to remove the FVP component from the “useful” total pressure of the fan, in other words, a FSP curve can be used for fans exhausting directly to atmosphere. This is the approach recommended by McPherson.⁷ As most simulation models require airways that are connected to atmosphere (as intakes or exhausts) to be specially identified, this adjustment to the FTP curve could easily be done internally by the simulation program.

If a ventilation officer only has available a simulation program that uses FSP, then the program can be made to work acceptably well by inputting FTP curves (adjusted for shock losses from the fans) rather than FSP curves, and then allowing one full velocity pressure loss from those airways that discharge directly to atmosphere, by using a shock loss of 1.0 at these outlets.

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