Deflectors for tunnel jet fans

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ABSTRACT

Deflection vanes are sometimes used to turn the discharged flow from jet fans away from tunnel surfaces, in order to counteract the Coanda effect and enhance the in-tunnel thrust. The aerodynamic effectiveness of such deflectors has been confirmed by a number of researchers over the last 30 years. This paper addresses the effect of deflectors on the in-tunnel thrust, as well as their effect on reducing jet fan bench thrust, increasing noise production and power consumption, the risk of structural failure due to fatigue, and extending the jet throw causing the buffeting of vehicles and pedestrians during use. It is concluded that the optimisation of deflector location and vane deflection angle can assist in mitigating, but not eliminating, some of the negative aspects of deflector use. Modern alternatives to vane-type deflectors have been developed, and have demonstrated superior performance under certain circumstances.

Keywords: *Deflectors, jet fan, thrust, Coanda effect, noise, fatigue, installation factor, power consumption*

1. INTRODUCTION

Jet fans serve to ventilate tunnels by discharging a high-speed jet, typically between 30 to 40 m/s velocity, and impart the jet's longitudinal momentum into the tunnel air. Depending on the location of the jet fan, part of that momentum (typically from 20% under arched soffits to 50% in rectangular corners) is dissipated due to friction between the jet and the bounding tunnel surfaces (soffit and walls). If the jet can be turned away from the tunnel surfaces to overcome the Coanda effect, the friction between the jet and the tunnel surfaces can be reduced, leading to an improvement in the in-tunnel thrust generated by the jet fans.

Several means of turning the discharged jet away from the tunnel surfaces have been developed and made commercially available, including slanted silencers ("Banana Jet®", Witt and Schütze, 2008) and shaped silencers ("MoJet®", Tarada et al, 2022), as well as project-related examples (e.g. Clark et al, 2013) . However, this paper is limited to consideration of deflector vanes. Such deflectors comprise an array of turning vanes, installed downstream of the discharge silencers. For reversible jet fans, deflectors are required at both ends of a jet fan if equal (or at least similar) thrust performance is required in reverse (Figure 1).

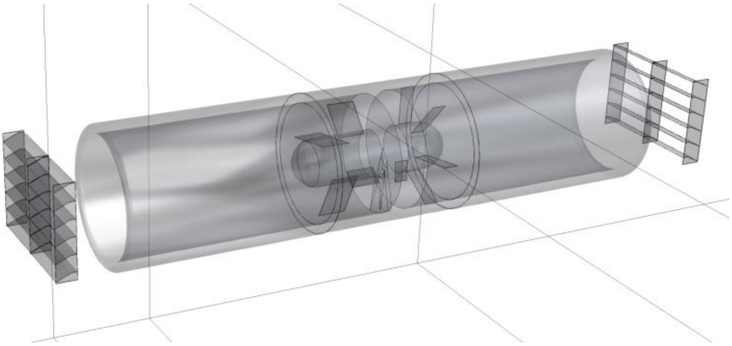

Figure 1: Reversible jet fan with deflectors

Another reason for using deflectors is to avoid the ingestion of discharged jets into downstream jet fans, which causes unloading of the fan blades and thereby a reduction in thrust. The use of deflectors permits closer longitudinal spacing between jet fans – from 10 tunnel hydraulic diameters without deflectors, to 6-8 tunnel hydraulic diameters with deflectors (PIARC, 1995).

2. PREVIOUS RESEARCH ON JET FAN DEFLECTORS

Costeris (1991) reported on the effect of deflectors on jet fans. His paper advised that the jet stream should be deflected by approximately 7.5°, in order to counteract the jet spreading to the nearest tunnel wall (Figure 2). In order to achieve that, the guide vanes should be angled by 10° to 13° from the horizontal. However, his view is that the installation of deflectors is not entirely beneficial. Deflectors generate an additional aerodynamic resistance of between 0.05 and 0.3 dynamic pressures, depending on where they are located downstream of the discharge silencer. This leads to a loss of thrust of at least 4% to 6% (and possibly more). He concludes that the installation of jet stream guide vanes can only considered to be an improvement if the advantages outweigh the drawbacks caused by the additional losses. In general, this is only the case if the jet stream guide vanes can operate under optimum conditions.

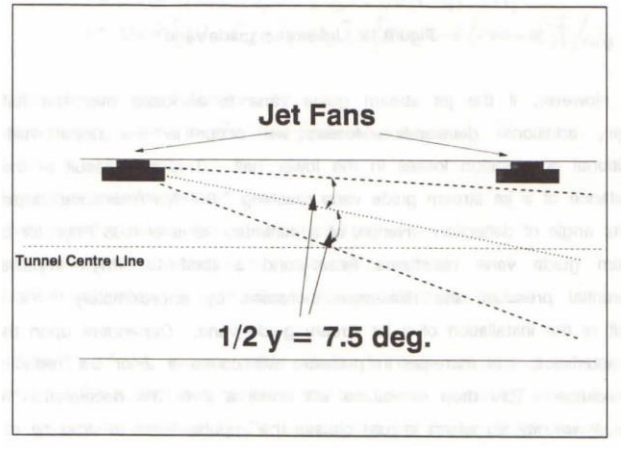

Figure 2: Idealised jet flow pattern with deflectors (Costeris, 1991)

Lotsberg (1997) reported a series of measurements with 1.5m internal diameter jet fans in the Fodnes tunnel in Norway. The installation of deflection vanes improved the jet fan installation factor (indicating the ratio of in-tunnel to bench thrust) from 60-70% to 85%, based on the average cross-sectional area of the tunnel. The measured air velocity profiles with deflectors over the tunnel height were much more even than those without deflectors (Figure 3).

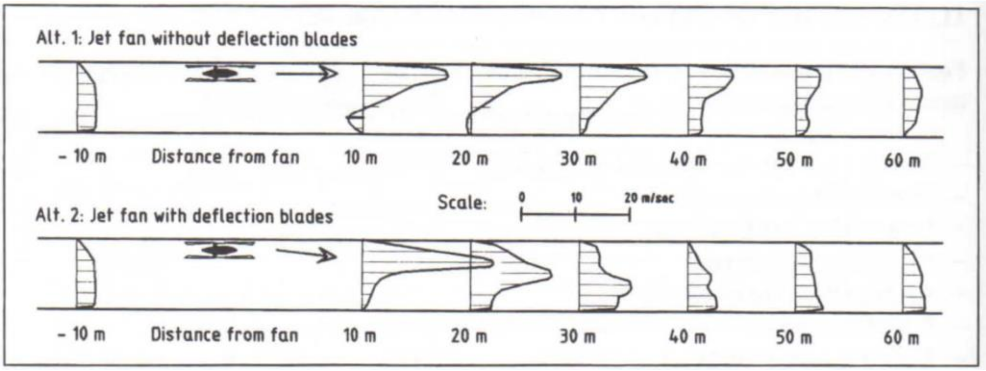

Figure 3: Measured velocity profiles in the jet fan plane (Lotsberg, 1997)

However, the area-average tunnel velocities with and without jet fan deflectors were not reported by Lotsberg, so it is not possible to quantitatively determine the improvement in the in-tunnel thrust with deflectors from his measurements. In addition, no comparison was provided for the jet fan bench thrust and power consumption with and without deflectors.

Beyer et al (2016) reported a series of measurements and CFD calculations for two jet fan installations in the Bosruck tunnel (1.6m internal diameter jet fans, with and without deflectors) and Niklasdorf tunnel (1.12m internal diameter jet fans, measured only without deflectors) in Austria. The Bosruck jet fans were installed immediately upstream of protruding tunnel headwalls (Figure 4). An improvement in the installation factor of more than 35% was measured in the Bosruck tunnel after the installation of deflectors, due to the avoidance of flow impingement on the headwalls. The authors reported a reduction in the bench thrust of up to 9% due to the installation of deflector vanes in the jet fans for the Bosruck tunnel.

Figure 4: Bosruck tunnel jet fans (Beyer et al., 2016)

To our knowledge, no comprehensive study has yet been reported on the effect of deflectors on jet fan thrust, noise and durability. This paper addresses some of these issues.

3. EFFECT OF VANE-TYPE DEFLECTORS ON JET FAN BENCH THRUST

In order to quantify the influence of deflectors on the bench thrust and sound power levels generated by jet fans, a series of experimental measurements were conducted on a 710 mm internal diameter jet fan driven by a 2-pole motor running at 2970 rpm, with 1-D silencers installed on both sides of the jet fan.

The first set of measurements involved testing the influence of deflector positioning, using a rectangular deflector with curved vanes with a deflection angle of 26°, as depicted in Figure 5. The fan blade pitch angle was set to 32° for this set of measurements. The forward flow direction was defined to be where the motor is downstream of the rotor, and the reverse flow direction is where the motor is upstream of the rotor.

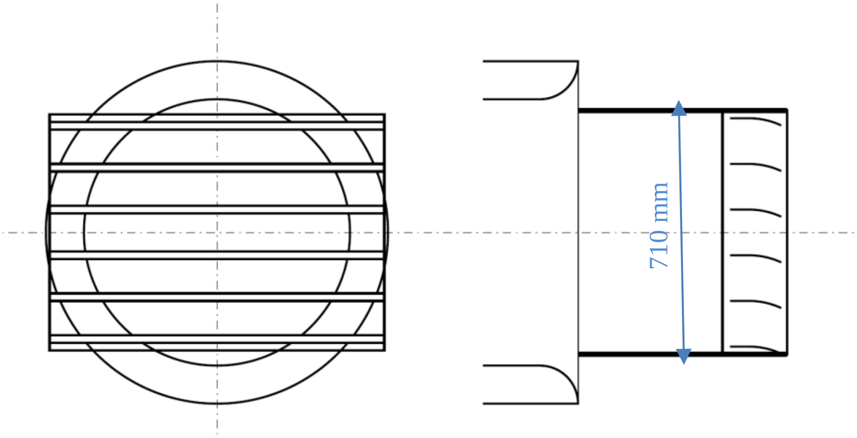

Figure 5: Rectangular Deflector used in Measurements

The jet fan was mounted on a thrust bench and measurements of longitudinal thrust were undertaken in accordance with ISO 13350:2015 “Fans - Performance testing of jet fans”. The baseline thrust, corresponding to the forward flow direction with no deflectors, was measured as 598.5 N. All thrust measurements were subject to an overall uncertainty (including systemic and random errors) of ±5 %. The results of this set of measurements are summarised in Figure 6.

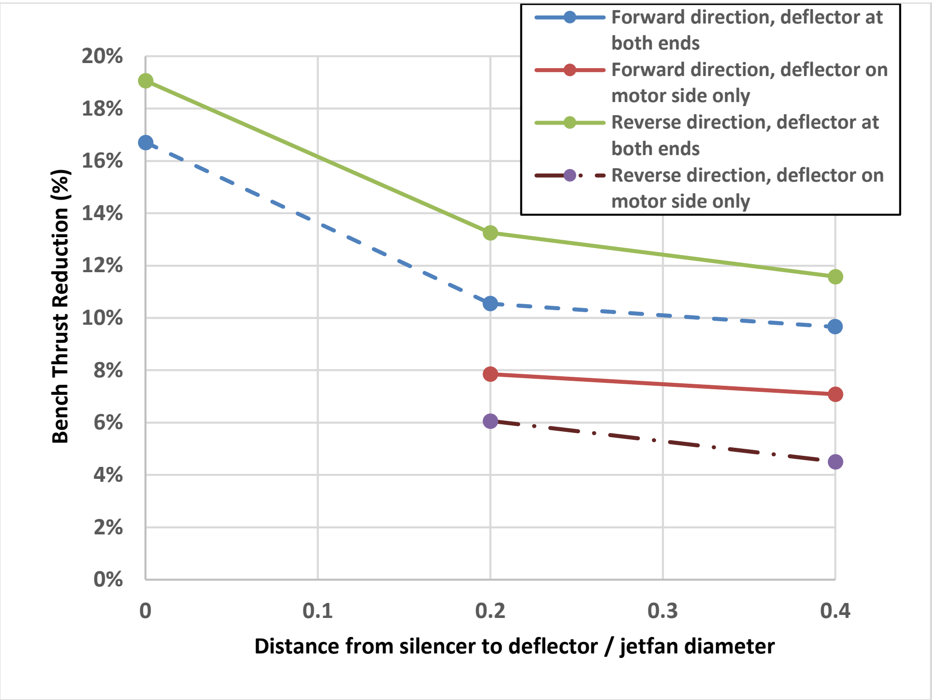

Figure 6: Thrust Reduction as a Function of Deflector Location

Figure 6 indicates that coupling the deflectors directly to the silencer ends is not recommended, since that can lead to thrust losses of nearly 20%. Increasing the distance between the silencers and the deflectors ameliorates the thrust reduction, but a thrust reduction of almost 10% was still observed with deflectors installed at 0.4D from both ends of the jet fan, for a forward flow direction (where D is the internal jet fan diameter).

Reduced thrust losses were observed for cases with deflectors installed only on one side of the jet fan – although that may not be suitable for reversible flow operation. With one set of deflectors installed at 0.4D from the discharge silencer, a thrust reduction of about 7% was measured. With one set of deflectors installed at 0.4D from the inlet silencer, a thrust reduction of 4.5% was measured - but no deflection of the discharged jet is obtained in that case.

In the second series of measurements, two different types of deflectors – namely rectangular (as previous) and circular, were measured using the same bench thrust rig. The fan blade pitch angle was set to 37° for this set of measurements, and the baseline thrust was 728.1 N. Figure 7 summarises the outcome of these measurements, which were all undertaken in the forward flow direction (i.e. with the motor downstream of the rotor).

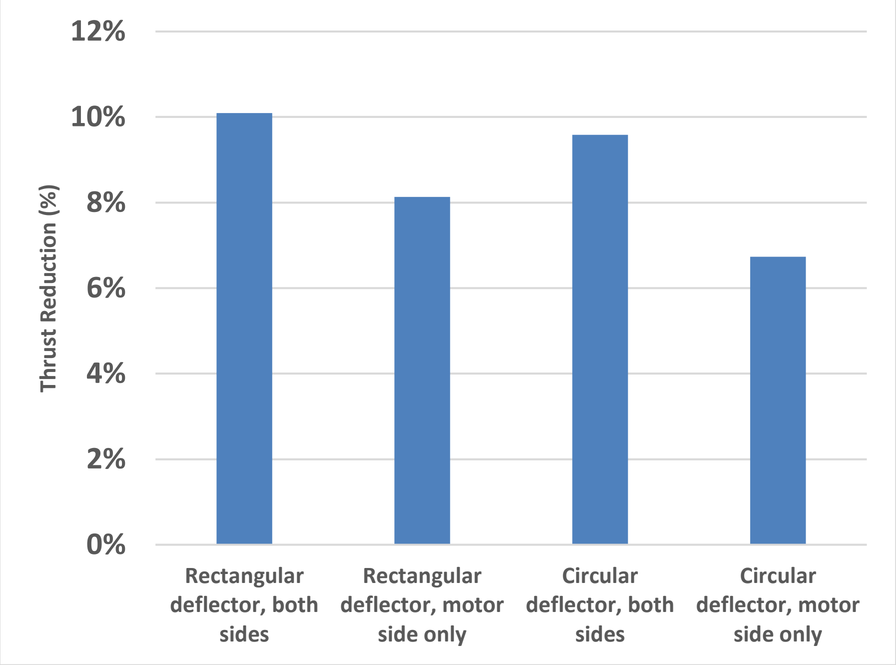

Figure 7: Thrust Reduction as a Function of Deflector Type and Installation

The results in Figure 7 indicate that the circular deflector exhibits marginally less thrust reduction (compared to the rectangular type) when installed on both sides of the jet fan, although the difference was within the range of experimental uncertainty. The reduction in thrust may be reduced by installing a deflector only on the discharge (motor) side, but this technique may only be relevant for unidirectional jet fans.

4. REGENERATED NOISE DUE TO VANE-TYPE DEFLECTORS

Air velocities of typically between 30 to 40 m/s are discharged from the jet fans and strike the vanes. This causes noise to be generated due to two effects: vortex shedding behind the vanes, and mechanical vibrations of the vanes.

The increase in sound power level due to the installation of deflectors was measured for the same sets of jet fan configurations measured in the previous section. The acoustic measurements were undertaken using an intensity probe on the inlet side of the jet fan, on the basis of ISO 13347-4:2004 “Industrial fans - Determination of fan sound power levels under standardized laboratory conditions - Part 4: Sound intensity method”. Measurement uncertainties were in accordance with ISO 13347-1:2004, ranging from 3 dB at 50 Hz down to 1.5 dB at 1000 Hz.

Figure 8 summarises the measurement results for the first set of measurements (undertaken with a fan blade pitch angle of 32°). The baseline sound power level for this set of measurements with no deflectors installed was 108.8 dB. The shape of the curves in Figure 8 was somewhat unexpected, in that a reduction in regenerated noise was observed by moving the deflectors away from the end of the silencers by 0.2D, but this was followed by an increase in noise levels when the deflectors were moved a further 0.2D away from the silencers. The reason for this behaviour is unknown, but may be due to fluid-structure interaction of the airflow with the deflector vanes.

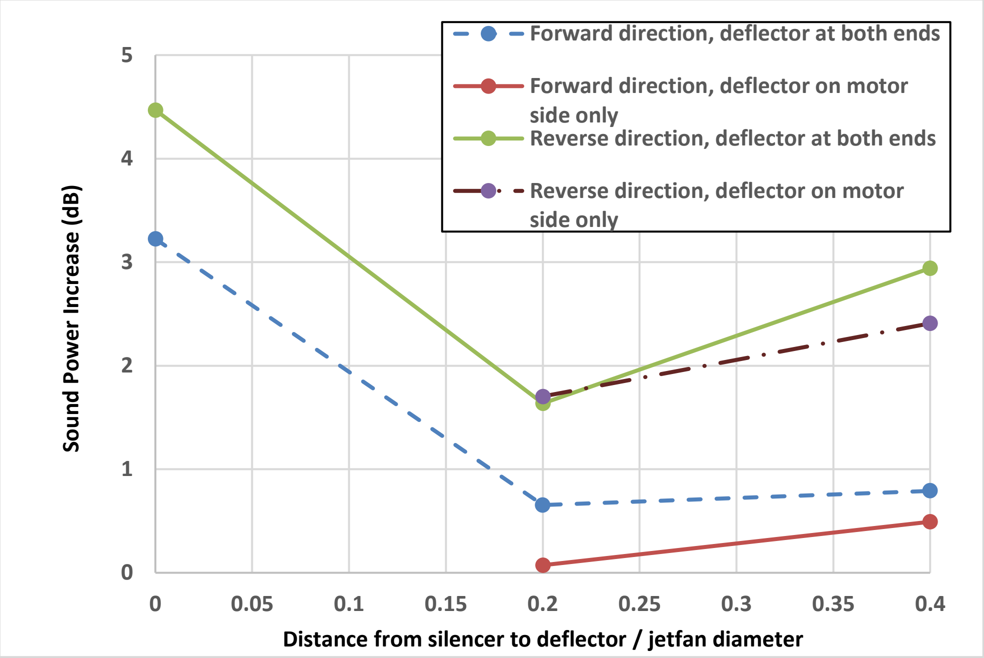

Figure 8: Sound Power Increase as a Function of Deflector Location

A second set of measurements were undertaken with a fan blade pitch angle set to 37°, with the deflectors installed at 0.4D from the silencers, and with flow in the forward direction only. A baseline sound power level of 109.7 dB was measured in the absence of any deflectors. Figure 9 summarises the results of the sound power level measurements for the two types of deflectors and installations (on one side of the jet fan or on both sides). The results established that the type of deflector made no significant difference to the measured sound power level. The least level of additional noise was generated with a circular deflector installed on the discharge (motor) side only.

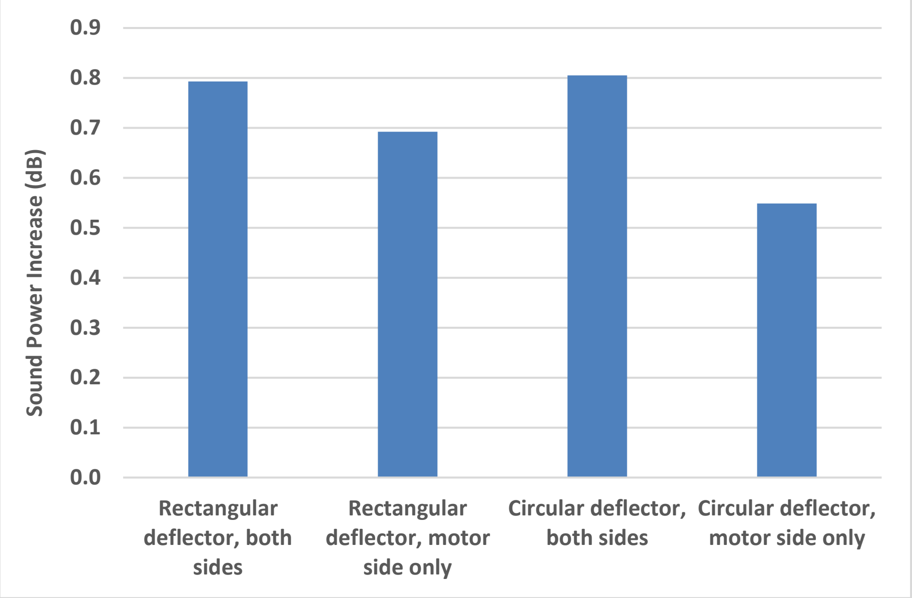

Figure 9: Sound Power Increase as a Function of Deflector Type and Installation

5. POWER CONSUMPTION

Due to the additional aerodynamic resistance imposed by the deflectors, the motor input power of the jet fans will increase, compared to the case without any deflectors. Measurements of the effect of deflection vanes on the motor input power of a jet fan were undertaken for the same conditions presented in the previous section. The measurements were made in accordance with ISO 13350:2015, and have an uncertainty range of ±2%. For the first set of measurements, the baseline input motor power with no deflectors installed was 18.2 kW, at a blade pitch angle of 32°. Figure 10 summarises the results of the measurements.

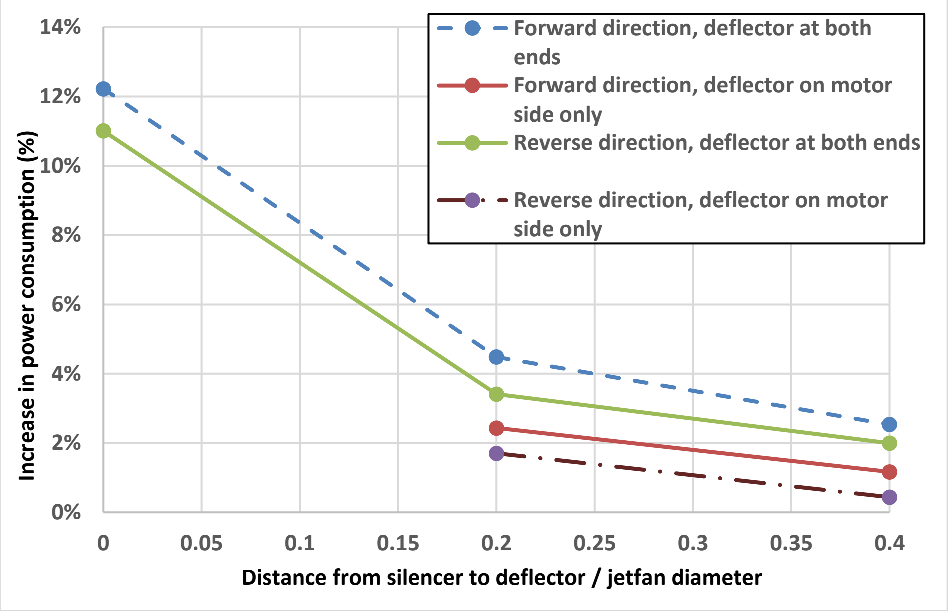

Figure 10: Increase in Motor Input Power as a Function of Deflector Location

Figure 10 confirms that the increase in motor input power reduces as the distance between the jet fan silencer and the deflector is extended. Nevertheless, a 4.5% increase in input motor power was recorded for airflow in the forward direction, with deflectors at both ends of the jet fan installed at 0.2D from the silencer.

A second set of measurements were undertaken with a fan blade pitch angle set to 37°, with the deflectors installed at 0.4D from the silencers and for a forward flow direction only. A baseline motor input power of 30.9 kW was measured in the absence of any deflectors. Figure 11 shows the results of this part of the investigation. This indicates that increases in motor input power can be ameliorated by the design of the deflectors, although only marginally.

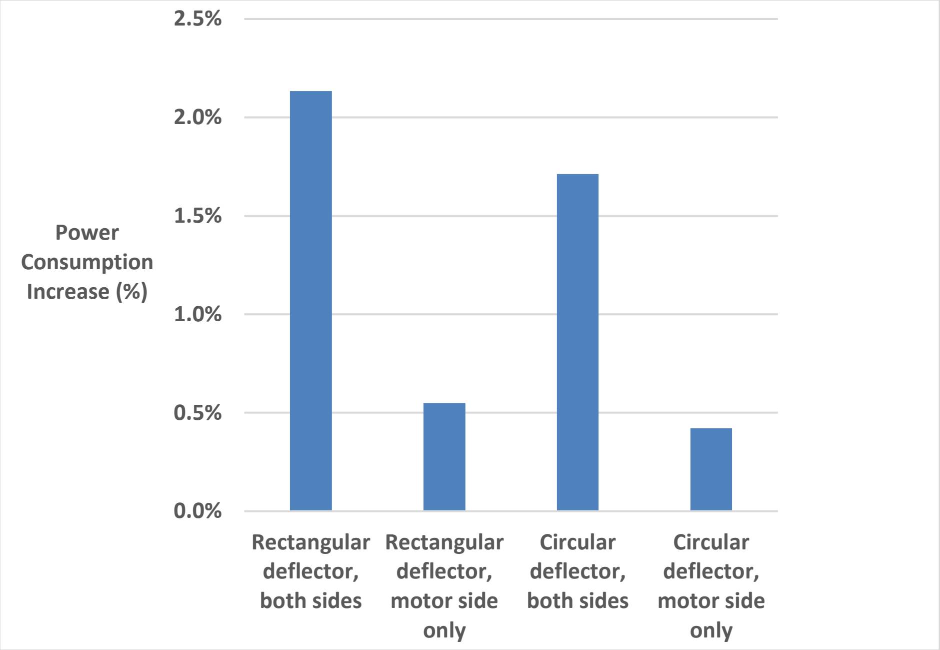

Figure 11: Increase in Motor Input Power as a Function of Deflector Type and Installation

6. STRUCTURAL INTEGRITY

The jet-induced excitation of the vanes causes them to vibrate at their natural frequency and multiples thereof. Depending on the natural frequency and the robustness of the fixings, the vanes may be prone to fatigue-induced failure.

The fatigue life of the deflector vanes can be assessed by the methods described in BS 7608:2014+A1:2015 “Guide to fatigue design and assessment of steel products”. This defines classes of welds, and predicts the fatigue life for each class at various stress levels using S-N curves. Welded joints between the deflector vanes and the frame are particularly vulnerable to failure through fatigue. If failures occur, they may potentially cause the vanes to fall onto moving traffic below, and this presents a safety risk.

A typical L_{10} bearing life (in accordance with ISO 281:2007 “Rolling bearings - Dynamic load ratings and rating life”) for a jet fan is 20,000 operating hours, and for safety reasons the deflector should have a significantly longer fatigue life than the bearing life, e.g. 100,000 operating hours. Tunnel inspections (undertaken to the Highways England (2020) CS 452 standard, for example) should prioritise the inspection of deflector vane joints on a risk-assessed basis.

7. JET THROW

The flow discharged from jet fans exhibits a high degree of swirl from the rotating blades. On the one hand, this swirl assists in dissipating the jet and imparting its axial momentum to the tunnel air within a short distance (which is generally a positive effect). However, the swirl also causes a more rapid expansion of the jet, which may then adhere to the neighbouring tunnel surfaces, due to the combination of swirl and the Coanda effect. If the jet is not deflected by vanes or other means, the discharge swirl may cause additional friction losses due to the attachment of the jet to the tunnel surfaces.

In general, deflection vanes tend to kill the swirl and hence significantly extend the jet throw. Depending on the vane deflection angle, this extended throw can cause the jet to attach to the tunnel floor, as shown by the 3D CFD calculations presented by Tarada and Else (2018). These calculations indicated that the aerodynamic friction between the jet and the tunnel floor can significantly reduce the jet fan installation factor, from 0.84 for a conventional jet fan to 0.60 for a jet fan with deflectors. Therefore the correct choice of deflector vane angle is important in maximising the in-tunnel thrust.

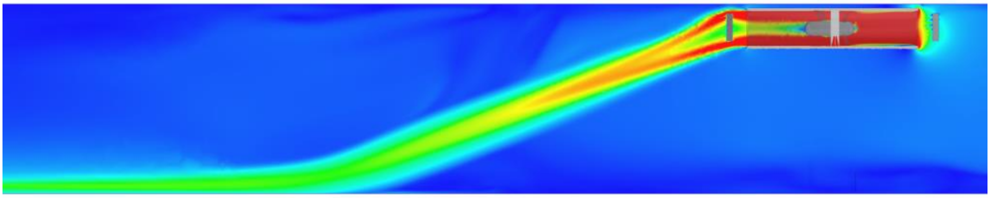

Figure 12: Velocity Contours with Deflectors (from Tarada and Else (2018))

The increase in jet throw when swirl is removed has been confirmed by Cozzi et al (2018). Figure 13 compares the time-averaged axial velocity profiles for jets with a low swirl number (*S*=0.45, typical for tunnel jet fans) with those for zero swirl (*S*=0). *S* is defined by Cozzi et al to be the ratio of axial flux of angular momentum to the axial flux of axial momentum multiplied by the nozzle radius, such:

$$S = \frac{\int_0^R r^2 \overline{UW} dr}{\left[\int_0^R r\left(\overline{U}^2 - \frac{1}{2}\overline{W}^2\right)dr\right] * R} \qquad \text{(Equation 1)}$$

where r is the local radius, R is the nozzle radius, U and W are the axial and azimuthal velocity components respectively.

At 2.5 jet diameters from the discharge plane, the peak axial velocity decays to approximately 60% of the bulk velocity with a low swirl number (*S*=0.45). In the zero swirl case, the peak axial velocity hardly decays – it still measures 90% of the bulk velocity at 2.5 jet diameters downstream.

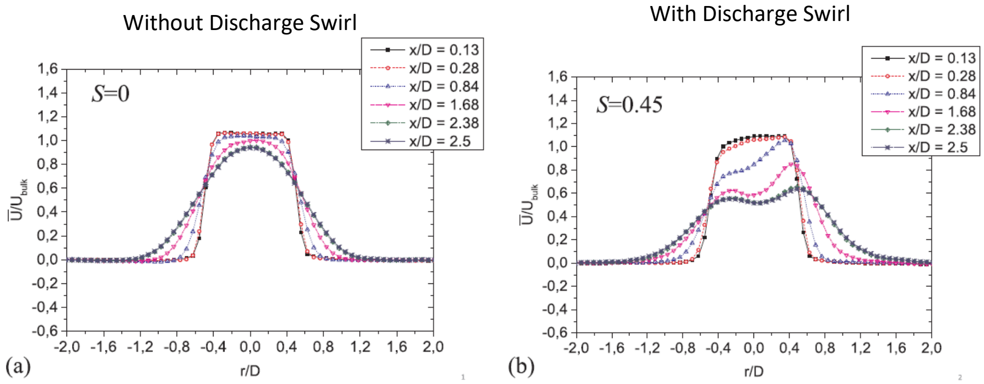

Figure 13: Effect of swirl on axial velocity profiles in an isothermal jet (Cozzi et al, 2018)

Measurements of jet throw undertaken by Strulik (2019) have shown that discharge swirl from nozzles can reduce the jet throw to less than half of the corresponding value with no swirl (Figure 14).

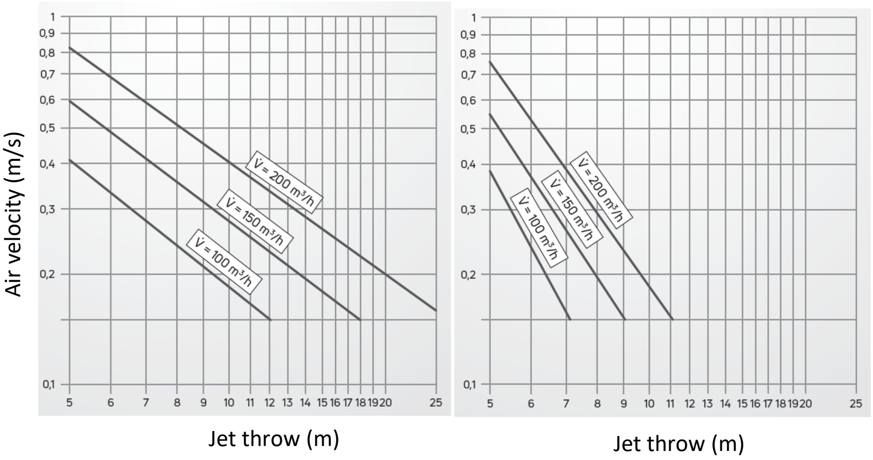

Figure 14: Effect of swirl on jet throw (Strulik, 2019)

The extended jet throw with deflectors may have negative consequences on vehicles travelling within the tunnel due to buffeting forces, particularly for high-sided vehicles such as heavy goods vehicles (HGVs) and vulnerable users such as motorcyclists. Pedestrians and emergency responders walking along the tunnel may be subjected to air velocities in excess of the recommended maximum. Both NFPA 502 “Standard for Road Tunnels, Bridges, and Other Limited Access Highways” and NFPA 130 “Standard for Fixed Guideway Transit and Passenger Rail Systems” (2020 editions) specify a maximum air velocity of 11 m/s within occupied zones, with NFPA 130 expressly stating that local, rather than area-averaged, velocities should be considered.

In addition to potential buffeting forces, another drawback from the use of vane-type deflectors is that the attachment of the jet onto vehicles such as HGVs in road tunnels and trains in rail tunnels increases the shear stresses along such vehicles and reduces the jet fan installation factor. For a non-swirling jet turned by 8°, Betta et al (2010) showed that the inlet tunnel velocity in a traffic jam fire scenario was less than the equivalent case with no turning of the jet. However, many ventilation system commissioning tests are undertaken in empty tunnels, where the effect of jet attachment onto stationary vehicles is not captured.

8. SHIPPING AND INSTALLATION WITHIN TUNNEL

Deflection vanes are slender bits of metal attached to an otherwise robust jet fan. In order to avoid damage during transit, it is common to separate the vanes from the jet fans during shipping. The vanes are then installed in-situ, after the jet fans have been hung onto the tunnel soffit. This is a further step that should be scheduled during the installation stage.

9. SUMMARY AND CONCLUSIONS

Vane-type deflectors potentially provide a significant advantage in improving the in-tunnel thrust delivered by jetfans. However, they can also produce penalties in terms of reduced jet fan bench thrust, increased noise production, higher power consumption, risk of structural failure due to vibration-induced fatigue and extended jet throw causing the buffeting of vehicles and pedestrians during use. The optimisation of deflector location and vane deflection angle can assist in mitigating, but not eliminating, some of these negative aspects. Modern alternatives to vane-type deflectors have been developed, and have demonstrated superior performance under some circumstances.

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