Design, Testing and Application of an Energy-Efficient Longitudinal Ventilation System

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This paper reports on the development, testing and application of jetfans with convergent nozzles to direct the flow towards the tunnel centreline, thus reducing the aerodynamic friction due to the Coanda effect. Since these nozzles do not protrude within the traffic space, a larger diameter fan running at a slower speed can be selected compared to jetfans with slanted silencers, and this configuration delivers a significant improvement in energy efficiency. An example tunnel ventilation application is highlighted, which indicates a 27% reduction in absorbed power. The effects of convergent nozzles on jetfans are demonstrated through CFD calculations on a road tunnel in London and the results of bench tests on a prototype.

1 INTRODUCTION

Longitudinal ventilation systems provide an airflow along the length of a tunnel, in order to satisfy air quality requirements or to control smoke movement in case of a fire scenario. Although there are different types of longitudinal ventilation systems for tunnels, the most widely used type is the one which employs jetfans to generate an aerodynamic thrust in the axial direction, and this is the subject of this paper.

Tunnel ventilation systems can absorb very significant amounts of energy, with some installations demanding several megawatts when all fans are switched on. Even if fans are not switched on (for example during periods of low traffic density), standing charges are normally applied in respect of the rated maximum power in a facility. The need to reduce emissions due to power generation and to combat greenhouse gases has given additional impetus to the quest for energy efficiency.

The development of an energy-efficient longitudinal ventilation system for tunnels has to consider two important aspects: fan efficiency, i.e. the proportion of electrical power that is used to accelerate a mass of air via an axial thrust, and the installation efficiency, i.e. the proportion of the fan thrust that is actually delivered to the tunnel air (rather than wasted via friction with the tunnel walls and soffit). A number of prior publications have considered these two effects separately.

In a paper reporting on inverter driven jetfans, Nakahori et al (2009) reported that fan power demand varies approximately with the cube power of discharge velocity, whereas the thrust only varies with the square of the discharge velocity. It therefore follows that a reduction in the discharge velocity can lead to a disproportionate decrease in power consumption. These findings echo those made earlier by Bopp (1994), who advocated speed control of jetfans for energy optimisation. Although these publications considered the issue of energy efficiency as a function of discharge velocity, it is possible to generalise their findings in order to ascertain the energy efficiency changes due to changes in fan diameter, for example.

The aerodynamic thrust provided by each jetfan may be approximated by

$$T = \eta_i \cdot \rho A_A v_A (v_A - v_\infty) \qquad \text{(Equation 1)}$$

where η_i is the installation efficiency, A_A is the cross section of the jetfan outlet, v_A the average fan discharge velocity and v_∞ the velocity in the tunnel beyond the direct influence of the jetfan intake and discharge.

The power demand P to drive a jetfan is given by

$$P = \frac{T v_A}{\eta_e} \qquad \text{(Equation 2)}$$

where η_e is the electrical efficiency of the motor (typically over 90% for three-phase motors in tunnel applications). The fan efficiency η_f can be defined as

$$\eta_f = \frac{P_t \dot{V}}{\dot{W}_s} \qquad \text{(Equation 3)}$$

where P_t = total pressure rise across the fan, $\dot{V}$ is the volumetric flowrate through the fan, and $\dot{W}_s = T v_A$ is the shaft power. η_f typically ranges between 40% to 70%, depending on a variety of parameters including: fan rotational speed, blade pitch angle, and the operating point on an fan's pressure-volume characteristic. Fan efficiencies for tunnel jetfans tend to lie towards the lower end of the specified range, since there is very little pressure drop across a jetfan, and fan efficiency tends to drop off at such low pressures (which some manufacturers term 'Full Intake & Discharge' or FID conditions).

If a fixed value of aerodynamic thrust is required while varying jetfan diameter and discharge velocity, it can readily be shown from equation (1) that fan diameter varies inversely with respect to discharge velocity (on the assumption that $v_A >> v_\infty$ and that η_i can be deemed constant). From equation (2), it follows that the power demand would be inversely proportional to fan diameter for a constant aerodynamic thrust (assuming constant η_f and η_e). The most energy efficient solution to providing a longitudinal ventilation system with jetfans would comprise:

- Maximising the fan diameter within the available space, and selecting the lowest discharge velocity consistent with the provision of sufficient aerodynamic thrust.
- Maximising the installation efficiency (η_i), fan efficiency (η_f) and motor electrical efficiency (η_m).

The installation efficiency η_i can be considered a measure of how much of the aerodynamic thrust is converted into useful work in accelerating the air in the tunnel, rather than being wasted due to friction between the discharge jet and tunnel surfaces (walls and soffit). Estimated in proportion to the installation efficiency, the fraction of energy that is typically wasted due to aerodynamic friction varies between 15% to 27% (Tarada and Brandt, 2009). The friction is exacerbated by the Coanda effect, which causes the high-speed jet to adhere to the tunnel surfaces.

In order to improve the installation efficiency, it is necessary to turn the discharge flow towards the tunnel centreline, and away from the walls and soffit. Previous recommendations to do this have included:

- Tilting the jetfans at up to 10°, as investigated by Woods Air Movement (1999). Such tilting was demonstrated to provide a significant increase in thrust at angles between 5° to 7°. However, tilting the jetfans may exclude the possibility of reversible fan operation, and may cause the fan housing to encroach upon the traffic space within the tunnel.

- Slanting the silencers at either end of a jetfan, in order to direct the flow towards the tunnel centreline (‘Banana Jet’). Marti and Brandt (2004) reported that installation efficiencies of near unity can be obtained with slanted silencers mounted at about 7° from the fan axis, although their reported measurement error was ±12 %. Slanted silencers may intrude upon the traffic space, or restrict the fan diameter that is possible to specify within a given equipment space.

- Installing deflection vanes at one or both ends of a jetfan, in order to direct the discharge flow downwards. Lotsberg (1997) reported from measurements in the Fodnes Tunnel in Norway that deflection vanes can be beneficial in reducing the Coanda effect, and in improving the installation efficiency from 60-70% to 90-95%. However, the paper notes that deflection vanes directly attached in front of the fan give a negative effect on fan performance (presumably through an increased pressure drop and power demand). It may reasonably be assumed that deflection vanes attached to the inlet of a fan would have a similar negative effect. If the deflection vanes are attached at some distance from the fan ends, the pressure drop and power demand are less affected, but only a proportion of the spreading jet may be captured and turned.

From the review outlined above, it would appear that both the fan efficiency and the installation efficiency should be considered when considering how to reduce the energy consumption due to jetfans. Although considered separately in the past, the two issues of fan and installation efficiency are actually closely inter-related.

2 JETFANS WITH CONVERGENT NOZZLES

Tarada (2008) described the concept of ‘momentum jets’ (MoJets) with convergent nozzles (silencers) on one or both sides of the fans, dependent on whether unidirectional or reversible jetfans are specified. By analysing a manufacturer’s fan characteristics, he argued that significantly greater aerodynamic thrust can be obtained with such convergent nozzles, by accelerating the discharged air into a smaller outlet area. Figure 1 shows a three-dimensional perspective of a reversible 1.25m diameter jetfan with convergent nozzles.

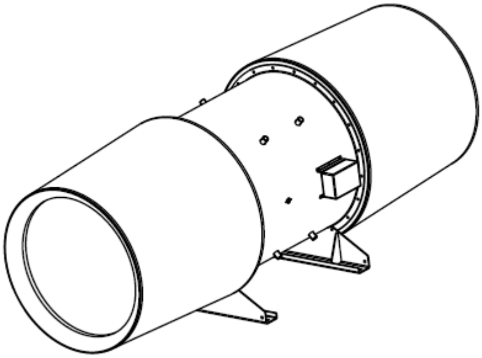


Figure 1: Reversible 1.25m jetfan with convergent nozzles

In addition to the thrust-enhancing effects of such convergent nozzles, it is also possible to turn the flow towards the tunnel centre-line and hence improve the installation efficiency. For a corner-mounted jetfan which has a typical installation factor of 0.73, the thrust enhancement can be up to 37% (estimated via (1-0.73)/0.73×100) and for a soffit-mounted jetfan, the enhancement can be up to 18% ((1-0.85)/0.85×100). For example, Figure 2 indicates a unidirectional jefan with convergent nozzles, with the centreline of the discharge nozzle turned at 5° relative to the fan axis.

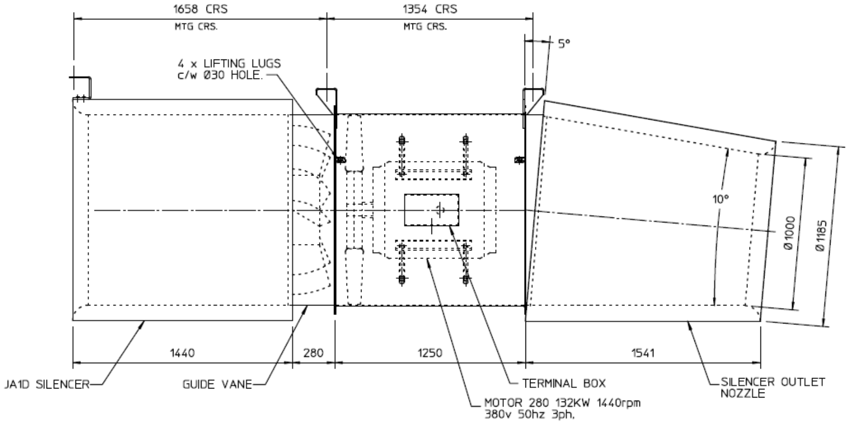


Figure 2: Unidirectional 1.25m jetfan with a convergent discharge nozzle

When comparing the energy efficiencies of jetfans with convergent nozzles and slanted silencers from the perspective of energy efficiency, it is important to consider the fan diameters that can be installed using the same equipment space. Convergent nozzles do not increase the fan envelope within the tunnel cross-section, but slanted silencers require an additional installation height of 12% for 1-D silencers, or 24% for 2-D silencers (assuming a 7° silencer slant). For a given equipment space, it follows that a jetfan with convergent nozzles can have a fan diameter up to 24% larger than those with slanted silencers, with the benefit of lower power consumption for a given thrust requirement (Equation 2).

Figure 3 shows a comparison between a 710mm diameter jetfan with slanted silencers and a 900mm diameter jetfan with convergent nozzles, both of which are rated to provide 454N of external thrust, and were designed to fit within the space in a tunnel wall/soffit corner. The jetfan with convergent nozzles was specified with a 4-pole motor as opposed to the 2-pole motor specified for the slanted silencer jetfan, which meant a 50% reduction in speed for the convergent nozzle jetfan. Compared to an absorbed motor power of 17.1 kW for the slanted silencer option, the convergent nozzle jetfan requires only 12 kW, representing a 30% reduction in absorbed power. This is due to the reduced discharge velocity and the improved fan efficiency at the selected operating point. It was also possible with the convergent nozzle jetfan option to dispense with the need for silencers, since the lower speed of the fan allowed the noise level to drop to 75 dB(A). The elimination of silencers represented a significant reduction in the product cost.

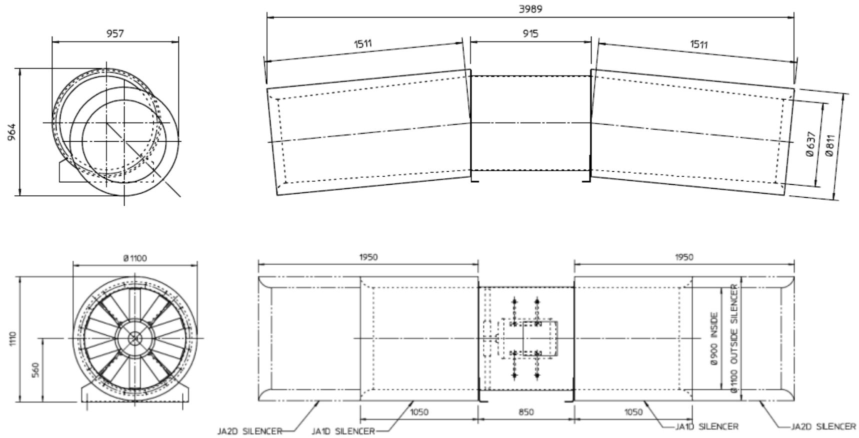
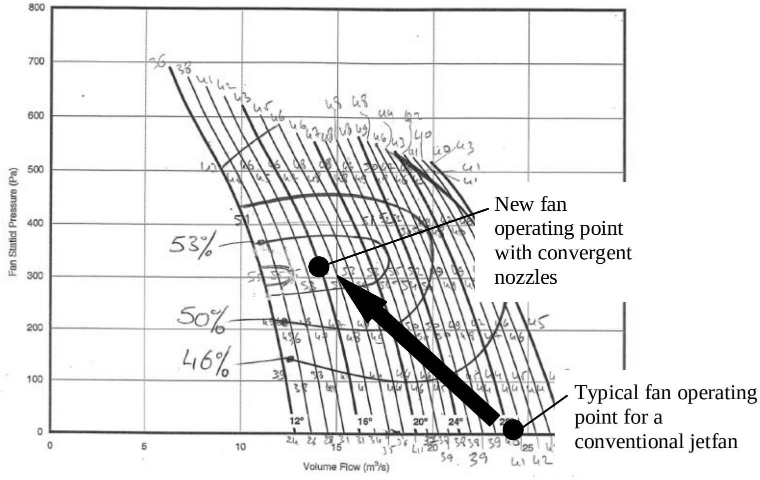


Figure 3: Comparison between 710 mm jetfan with slanted silencers and a 900mm jetfan with convergent nozzles

In general, it is possible to select convergent nozzle jetfans with improved fan efficiencies compared to conventional jetfans and slanted silencer jetfans, by operating at smaller blade pitch angles and higher pressure drops, while still delivering the required aerodynamic thrust. Figure 4 indicates the general fan design strategy for jetfans with convergent nozzles.



New fan operating point with convergent nozzles

Typical fan operating point for a conventional jetfan

Figure 4: Fan Efficiency Contours for 1120mm bidirectional jetfan (1440 rpm, 9 blades)

3 SOURCES OF FAN PRESSURE LOSSES

In considering the energy efficiency of jetfans, it is important to consider the sources of irreversibility due to aerodynamic friction within the internal components of a jetfan. These considerations allow a comparison between different design options to be made.

The main pressure drop through a jetfan is at discharge, where one velocity head $(\rho v_A^2/2)$ is assumed to be destroyed. Although convergent nozzles cause an increase in the discharged velocity head, this should not be considered an increase in the irreversibility, since the kinetic energy of the jet is employed to accelerate the tunnel air.

Both slanted silencers and convergent nozzles create an increase in the air velocity within the silencers/nozzles, the former due to the separated zones in the vicinity of the junctions between the fan and the nozzles, and the latter due to the convergence in cross-sectional area which leads to an increase in air velocity. These increases in velocity raise the skin friction drag within the silencers/nozzles compared to a conventional jetfan, and represent a source of irreversibility. The key issue is whether these irreversibilities are offset by the energy-saving benefits outlined earlier.

Table 1 provides estimates of the loss coefficients for the inlet and discharge components within jetfans. The estimates were based on the correlations provided by Idelchik (1994) and cross-checked with typical fan operating points. Table 1 does not include estimates of losses due to aerodynamics effects at the fan rotor and motor, since such losses are deemed to be reflected in the fan performance characteristics.

Component	**Loss coefficient based on discharged velocity head**	**Assumptions**
Outlet pressure loss	1	
Inlet bellmouth	0.250	Jetfan bellmouth
Inlet silencer (baseline, straight)	0.010	1-D silencer
Outlet silencer (baseline, straight)	0.010	1-D silencer
Convergent nozzle	0.012	Nozzle area ratio of 1.36, 1-D silencer
Divergent nozzle	0.014	Nozzle area ratio of 1.36, 1-D silencer

Table 1: Estimated loss coefficients through jetfan components

From Table 1, we may conclude that the additional pressure losses due to convergent and divergent nozzles are small, compared to the large energy-saving benefits outlined above. In selecting the appropriate nozzle area ratio, it is important to avoid separation of flow within the divergent (inlet) nozzle, by maintaining the nozzle surface angles to 10° or less.

4 CFD CALCULATIONS

A number of CFD calculations were undertaken to compare the performance of convergent nozzle jetfans with conventional jetfans for an existing 1.5 km long road tunnel in London, which is due to be refurbished (Figure 5). The objective of the CFD calculations was to consider whether the turning of the flow within a jetfan with convergent nozzles was sufficient to reduce the Coanda effect.

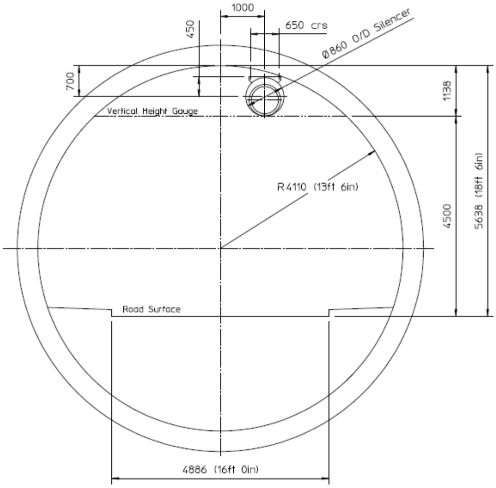


Figure 5: Cross-section of tunnel, ventilated by jetfans incorporating convergent nozzles

In order to adequately capture the physics of the situation, the flows within the tunnel and through the jetfans were modelled, including the fan rotor (Figure 6). This allowed the effects of swirl on the flow discharged from the jetfan to be modelled.

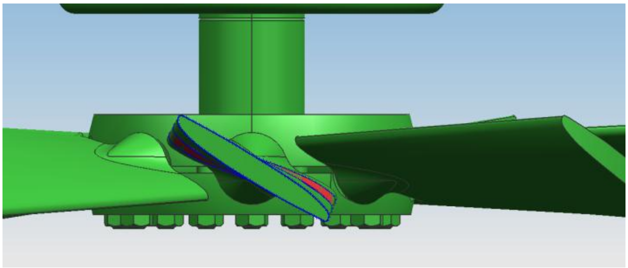


Figure 6: Fan Rotor Modelled within CFD

A 100m length of tunnel was modelled, with the fans located at 20m from the inlet portal (Fig. 7). This was to allow the jet to mix out reasonably well across the cross-section of the tunnel by the time it reached the outlet portal.

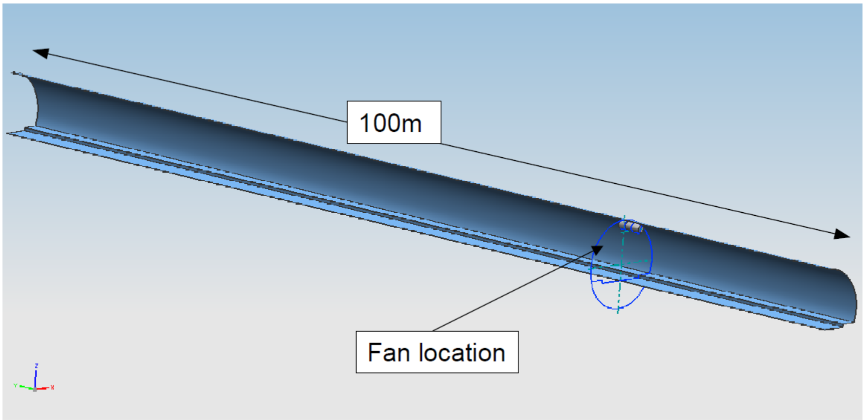


Figure 7: Location of fans within tunnel in CFD geometry

The calculations were undertaken using a commercial CFD code (CFX). A standard k-ε model of turbulence was selected, and mixing planes was employed at the boundaries between the rotational (fan) and stationary parts of the calculations domain. Boundary layers on the tunnel surfaces were resolved using geometrically expanding hexahedral meshes. The core of the tunnel was meshed using tetrahedral elements. The total number of cells used in the calculations was approximately 2 million.

The results of calculations indicated that the discharge jet was indeed turned away from the tunnel soffit, and that there was a marked reduction in the Coanda effect. Figure 8 indicates a typical streamline and velocity contour plot obtained, which showed that the flow from the convergent nozzle remained away from the tunnel surfaces, rather than adhering to them. The concept of employing convergent nozzles to reduce the Coanda effect was thus supported by these calculations, for this particular tunnel application.

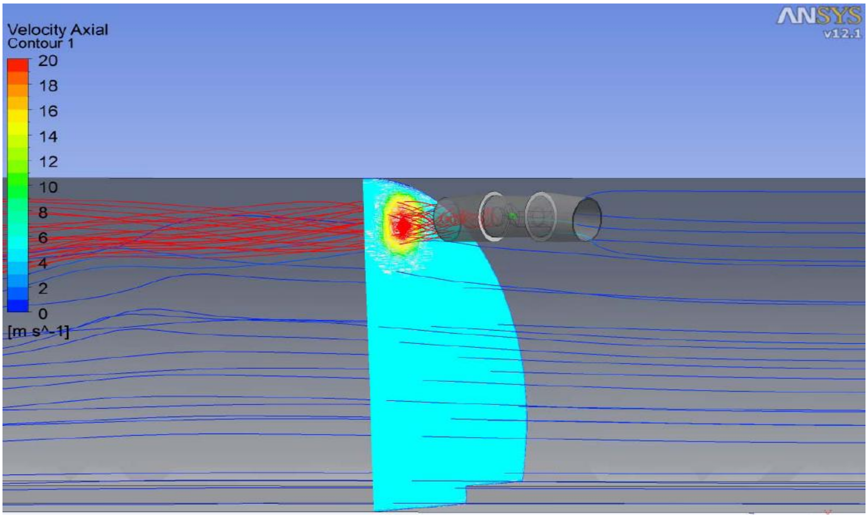


Figure 8: CFD calculations of flow turning through jetfans with convergent nozzles

5 PROTOTYPE MEASUREMENTS

In order to ascertain the effects of convergent nozzles on aerodynamic thrust and noise, a number of bench tests were undertaken with a 1m diameter jetfan with 20° blade pitch angle and a 50 Hz 4-pole motor, in accordance with BS 848-10:1999. A nozzle area convergence ratio of 1.6 for both sides of the jetfan was chosen, based on prior calculations which considered the expected fan characteristic. Straight silencers were manufactured as well, in order to compare the effects of straight and convergent silencers. Both 'Form A' (flow drawn over motor) and 'Form B' (flow pushed over motor) thrust tests were conducted, along with acoustic measurements of noise. The allowable measurement uncertainty in the thrust measurements was ±5%, and that for the input power was ±2%.

Mean values measured in Form B			Mean values measured in Form A			Comments
Input Power	Current	Thrust	Input Power	Current	Thrust	
8.89 kW	18.43 A	281 N	8.89 kW	18.43 A	280 N	Straight nozzles
8.37 kW	17.88 A	299 N	8.16 kW	17.60 A	299 N	Convergent nozzles (area ratio 1.6)

Table 2: Summary of Prototype Measurement Results (1m diameter fan)

The measurements from the 1-m fan prototype tests indicate a 7% increase in static thrust and a 7% reduction in power consumption, indicating a 15% improvement in energy efficiency.

Separate measurements of sound pressure levels 1m away from a 1.25m fan with straight silencers indicated 92 dB(A). The measurements with convergent silencers on the discharge side gave 91 dB(A), while those with convergent silencers on both sides of the fan produced 90 dB(A). The reduction in sound pressure levels due to the installation of convergent silencers was somewhat surprising, but these variations are within the 3 dB measurement uncertainty specified in BS ISO 13347-1:2004. It is speculated that the reduction in sound pressure level downstream of a convergent nozzle may be due to the increased occlusion of the fan blades with respect to the outside environment, and the promotion of internal sound reflections within the silencer.

6 DESIGN APPLICATION

Jetfans with convergent nozzles were recently designed for an underground railway project in order to reduce the required number of jetfans and also to improve energy efficiency (Figure 9). The conventional design used jetfans with straight silencers installed within the tunnel corners, for which an installation factor of 0.73 was assumed (following Kempf, 1965). Table 3 provides an overview of the design parameters. In this application, jetfans with convergent silencers require only 77% of the in-tunnel thrust of conventional jetfans, due to the reduction in the Coanda effect.

	Standard Jetfan	Jetfan with convergent silencers
Design Thrust Requirement (in Tunnel) incl. velocity factor	22,803 N	
Installation Factor	0.73	0.95
Static Thrust Requirement (N)	31,237	24,003
Maximum Fan size	710mm diameter	

Table 3: Comparison of design parameters

Based upon the above-mentioned design parameters, fan selections were undertaken, as indicated in Table 4. The power consumption per fan was reduced by 13% by using convergent nozzles. Since fewer fans were required when using convergent nozzles, the overall power consumption for the tunnel was reduced by 27%.

	Standard Jetfan	Jetfan with convergent silencers
Selected Fan	710TR 2P	710TR 2P
Fan Thrust (N)	822	758
Fan Quantity	38	32
Absorbed Power per Fan (kW)	32.8	28.6
Overall Power Absorbed (kW)	1246.4	915.2

Table 4: Fan Selections

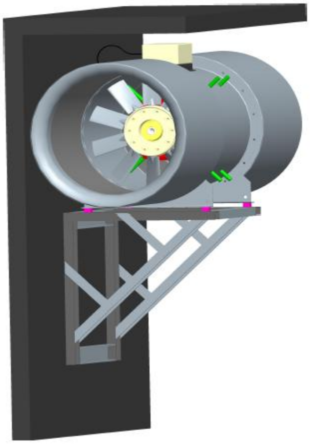


Figure 9: Jetfan with bidirectional convergent nozzles

7 CONCLUSIONS

The quest for energy efficiency in longitudinal tunnel ventilation systems with jetfans leads us to consider the influence of fan and installation efficiencies as well as the selection of fan diameters within the available equipment space. The employment of convergent nozzles on jetfans to direct the flow towards the tunnel centreline was shown by CFD modelling to significantly reduce the Coanda effect, and hence improve installation efficiency by up to 37% (based upon a corner-mounted jetfan). Larger diameter jetfans discharging jets with lower velocities can be specified in jetfans with convergent nozzles compared to those with slanted silencers, and the increase in diameter alone can reduce power demand by up to 24%. The operation of fans at a higher pressure point and at lower blade pitch angles allows an improvement in fan efficiency of up to 15% to be achieved.

Prototype measurements of a 1m diameter jetfan with a convergent nozzle ratio of 1.6 indicated that the bench-measured thrust increased by 7%, with a reduction in power consumption of 7% compared to a jetfan with a straight silencer. Due to the compound benefits of reductions in the Coanda effect and enhancements in fan efficiency, reductions in energy consumption of 27% were demonstrated for a railway tunnel project.

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