Jet Fan Installation Factors

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ABSTRACT

A review of estimates for jet fan installation factors previously published by Kempf (1965), Cory *et al* (1997) and Beyer *et al* (2016) indicates significant limitations or shortcomings in their applicability for tunnel ventilation design. We use an experimentally validated 3D CFD model to investigate installation factors for corner- and soffit-mounted conventional jet fans and those with shaped silencers ("MoJet"), for a range of tunnel air velocities, three different clearances to the tunnel surfaces and for two jet fan diameters (710 mm and 1250 mm). The results confirm the utility of deflecting the discharge jet away from the bounding tunnel surfaces to enhance the in-tunnel thrust, by reducing the shear stress at the tunnel surfaces and to minimise the ingestion of high-speed air into downstream jet fans.

Keywords: *Jet fan, thrust, Coanda effect, installation factor*

1. INTRODUCTION

Longitudinal ventilation via jet fans is an increasingly popular method of ventilating tunnels, due to its initial investment cost advantages compared to alternative methods, such as shaft-based fans. Originally limited to the ventilation of relatively short tunnels of around 3 km or less, recent projects such as the 18 km Fehmarnbelt Tunnel connecting Germany to Denmark will use jet fans in both the road and rail tunnel cells (Exarchakos *et al*, 2011). Although the initial investment costs for jet fans may be lower than those for shaft-based fans, operating and maintenance costs for jet fans may be higher than shaft fans. This is due to the relatively low installed efficiencies of conventional jet fans, and because of the difficulty in accessing jet fans installed above traffic lanes for maintenance and replacement purposes. One method that has been successfully employed to improve the installed efficiency of jet fans is the use of shaped silencers ("MoJet"), as demonstrated in the Mersey Queensway Tunnel (Tarada *et al*, 2022).

A key measure of jet fan efficiency is the ratio between the in-tunnel thrust and bench thrust generated by jet fans, which is commonly referred to as the jet fan installation factor. This paper comprises a review of commonly used engineering correlations of installation factors, the validation (with respect to experimental measurements) of 3D CFD calculations of installation factors and the presentation of estimates of installation factors for different jet fan installations, based on CFD.

2. JET FAN INSTALLATION FACTOR – DEFINITION AND INFLUENCING FACTORS

Following PIARC (1995), the jet fan installation factor η_i is used to calculate the in-tunnel value of thrust (T) using the following equation:

$$T = \eta_i \rho A_j V_j (V_j - V_T) \qquad \text{(Equation 1)}$$

where A_j is the cross section of the jetfan outlet, V_j the average axial velocity of the discharge jet and V_T the velocity in the tunnel beyond the direct influence of the jetfan intake and discharge. There is an expectation that η_i should be below unity, although it is theoretically possible for values slightly above unity to be obtained (Tarada and Brandt, 2009). Although Equation 1 was developed for conventional jet fans, the same formulation can be used for jet fans with shaped silencers, with cross-sectional areas and axial velocities based on equivalent conventional jet fans. This on the basis that any thrust lost due to the reduction of jet velocity within the shaped discharge silencer would be recovered through an increase in the local static pressure (by reference to the Bernoulli equation).

Costeris (1991) summarised some of the main factors influencing the jet fan installation factor. These include:

1. Aerodynamic friction between the discharged jet and the neighbouring tunnel surfaces (soffit and walls);
2. Unloading of jet fans due to ingestion of high-speed jets from upstream fans;
3. The geometry of any tunnel niches used for the installation of jet fans.

An additional factor affecting the installation factor is the lateral spacing between adjacent jet fans at the same tunnel chainage, if jet fans are arranged in banks. Close lateral spacing (below approximately 1.5 jet fan diameters) of jet fans can lead to additional turbulence due to the collision of swirling discharge jets, and hence a loss of in-tunnel thrust.

3. PREVIOUS RESEARCH ON JET FAN INSTALLATION FACTORS

Kempf (1965)

The first systematic study of jet fan installation factors was undertaken by Kempf (1965) at the Institute of Aerodynamics in ETH Zürich. He used a 1:60 scale model to measure the effective tunnel thrust for corner-mounted nozzles, as depicted in Figure 1 and Figure 2. A 16mm nozzle was installed within a 200mm square wind tunnel to simulate the effect of a jet fan installed in a tunnel. The measurements were undertaken with the nozzle located at various horizontal and vertical clearances from the wind tunnel corner, as well as within a niche (Figure 2).

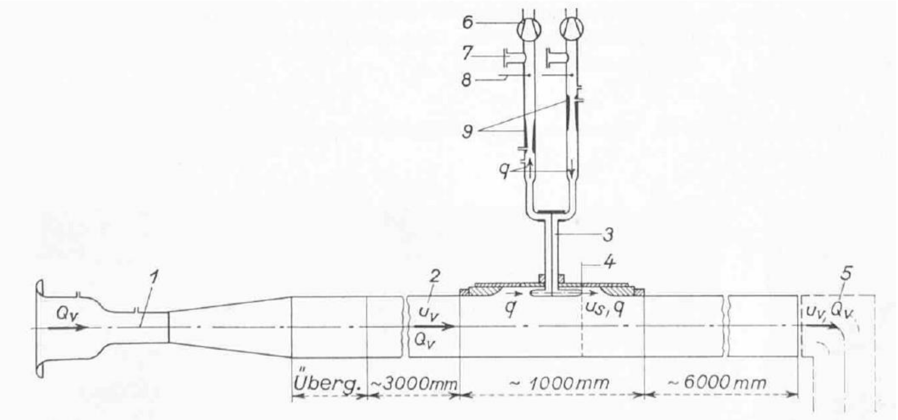


Figure 1: Test equipment used by Kempf (1965)

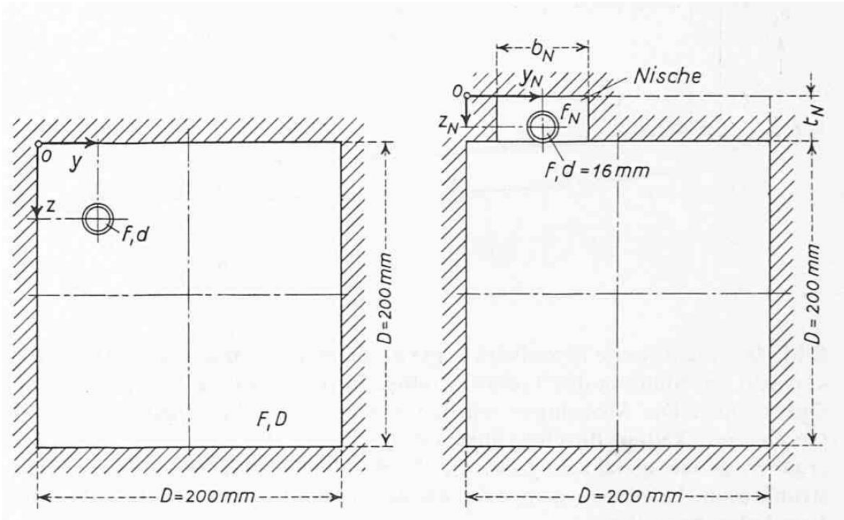


Figure 2: Nozzle locations measured by Kempf (1965)

Although Kempf himself did not correlate his results for installation factor, later researchers attempted to do so. For example, Tarada and Brandt (2009) presented the following correlation for the jet fan installation factor:

$$\eta_i = \left[0.0192\left(\frac{z}{D_A}\right)^2 - 0.144\frac{z}{D_A} + 1.27\right]^{-1} \qquad \text{(Equation 2)}$$

where D_A is the outlet diameter of the jetfan and z denotes the distance between the centre axis of the jet at the outlet and the tunnel wall.

Although Kempf's results are still widely quoted in the tunnel ventilation literature, they suffer from a set of drawbacks. His jet Reynolds numbers are approximately 50 times smaller than reality, which significantly affects the shear stress generated at the tunnel surfaces. His discharged jet had no swirl, hence it would have expanded more slowly than a jet issued from a conventional jet fan and was less likely to attach to the tunnel wall or soffit – hence making his results over-optimistic. The partial choking effect of a jet fan at close proximities to a wall or corner was not properly captured, since a large external fan was used. Kempf only used one nozzle, hence no downstream jet interaction or sideways interference effects can be established from his results. Another drawback from Kempf's results is that the effect of tunnel air velocity on the installation factor, which has been demonstrated by later researchers including Beyer *et al* (2016), was not measured. On that basis, it would be unwise to rely upon Kempf's measurements for any jet fan designs.

Cory *et al* (1997)

A series of tests were carried out on a 1/15 scale model by Cory *et al* (1997) with a 13.45m long rectangular duct in order to investigate the effects of jet fan clearance from the tunnel soffit and jet swirl on installation efficiency. A 64 mm diameter pipe fed by a centrifugal fan positioned at the tunnel portal was used to simulate a jet fan (Figure 3). Cory *et al* reported the effects of jet fan clearance on "jet fan efficiency" (Figure 4), which is in this paper's parlance is the product $\eta_i(\nu_A - \nu_T)$.

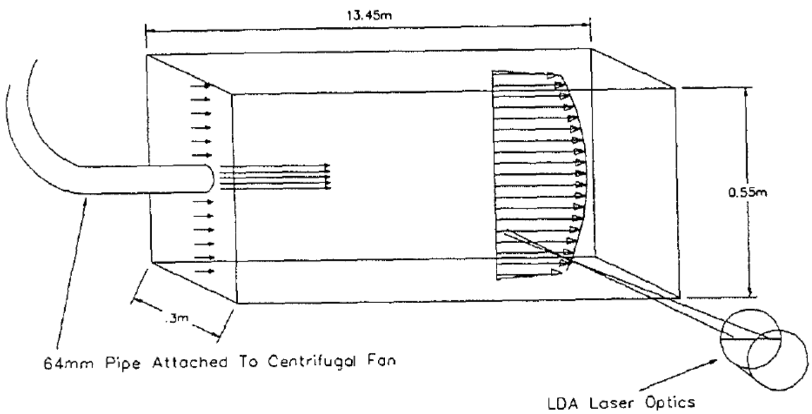


Figure 3: Experimental layout investigated by Cory *et al* (1997)

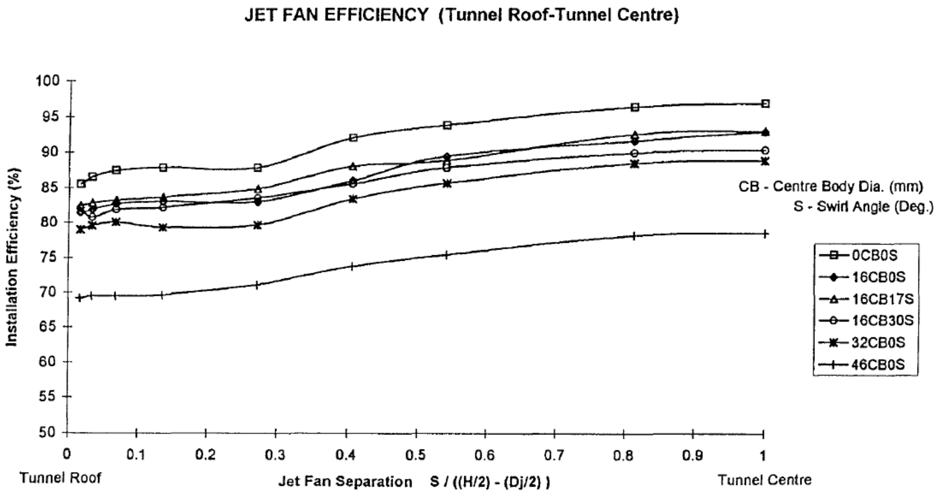


Figure 4: Effect of jet fan clearance on efficiency (Cory *et al*, 1997)

Cory *et al*'s results were reformulated for jet fan design by Woods Air Movement (1999), showing the effect of wall proximity on installation factor for both corner and ceiling (soffit) installations (Figure 5). This reformulated correlation is still widely used for jet fan design.

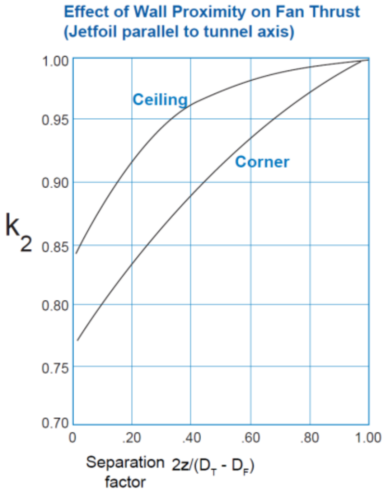


Figure 5: Effect of wall proximity on jet fan thrust (Woods, 1999)

Due to the selected model scale, the jet Reynolds numbers reported by Cory *et al* were approximately 15 times (i.e. more than one order of magnitude) less than reality. This has significant consequences for the confidence that can be placed on their results for jet fan design. In particular, their conclusion that swirl has no effect on jet fan installation factor is questionable, if more realistic jet Reynolds numbers are applied. No suction effects were represented at the inlet, therefore the partial choking effect of a jet fan at close proximities to a wall or corner was not captured. The flow profile at the inlet to the duct was not fully developed, in contrast to typical jet fan locations in tunnels. In addition, Cory *et al* only used a single nozzle to model a jet fan, and did not consider any jet interaction or interference effects. They did not report any variations of installation factor with respect to tunnel velocity. On that basis, we conclude that Cory *et al*'s measurements are not a reliable basis for tunnel ventilation design.

<u>Beyer *et al* (2016)</u>

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. Based on these measurements, they developed and validated a numerical CFD model. The validated CFD model was then used to analyse jet fan installation efficiency with deflectors. Investigations showed that apart from wall clearance, jet fan size, etc. the installation efficiency is strongly dependent on the air velocity in the tunnel (Figure 6). They also found that the installation factors were consistently lower than those measured by Kempf (1965).

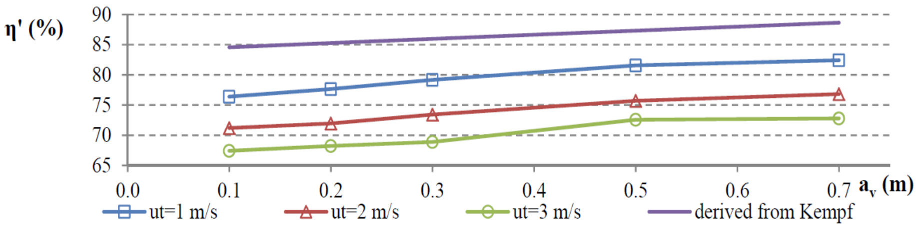


Figure 6: Effect of soffit clearance (a_v) and tunnel air velocity on installation factor (Beyer *et al*, 2016)

Since Beyer *et al*'s CFD predictions assumed no discharge swirl downstream of the turning vanes, their CFD results do not apply for conventional jet fans (i.e. without deflection vanes), nor do they apply for jet fans with shaped silencers ("MoJet"). The installation factors presented by Beyer *et al* do not account for the fact that turning vanes reduce the jet fan bench thrust by up to 19%, depending upon their design (Tarada, 2022).

Tarada *et al* (2022)

Tarada *et al* (2022) presented measurements and CFD calculations of a 1.25 m internal diameter conventional jet fan and the same fan with shaped silencers ("MoJet") installed in the Rendel Street branch of the Mersey Queensway Tunnel (Figure 7).

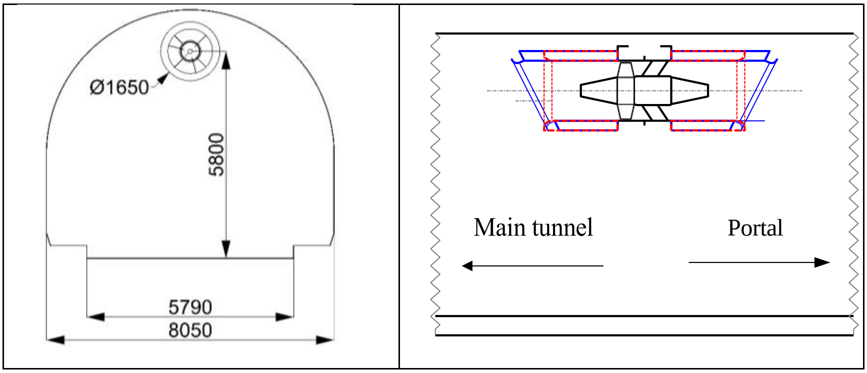


Figure 7: Installation of jet fan in Mersey Queensway Tunnel (red=conventional jet fan, blue=MoJet), with dimensions in mm

The right-hand side of Figure 7 shows the difference between the outlines of a conventional and MoJet silencer. MoJets have silencer inlets and outlets that are tilted, in comparison with conventional silencers which have vertical inlets and outlets. Bellmouths are attached to the tilted silencers, and these have the effect of deflecting the flow downwards (on the discharge side) and avoiding flow separation (on the inlet side).

Tarada *et al* (2022) presented curves showing the variation of installation factors with respect to tunnel air velocity for the two types of jet fans (Figure 8). Significantly higher installation factors were reported for the MoJet compared to a conventional jet fan. The general trend of reducing installation factors as a function of increasing tunnel velocity was confirmed.

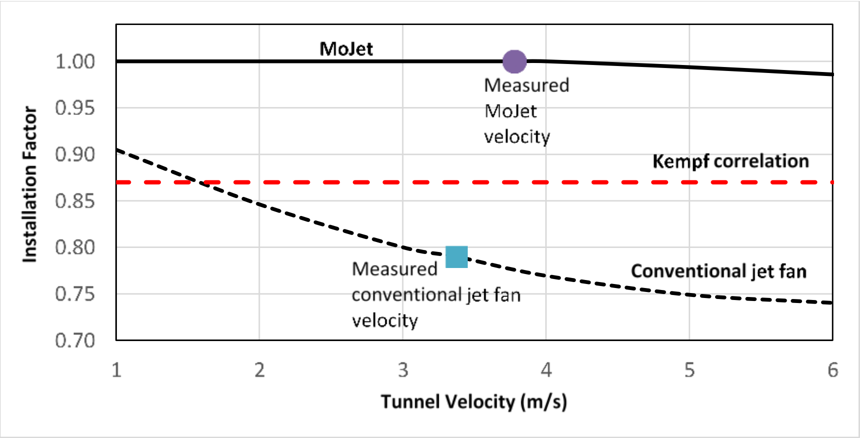


Figure 8: Jet fan installation factors estimated by Tarada *et al* (2022)

4. CFD SET-UP

<u>General approach and verification</u>

In order to estimate the jet fan installation factors for a variety of geometrical and tunnel flow conditions, we used the same CFD modelling approach as that employed by Tarada *et al* (2022). This comprised using ANSYS Fluent version 2022 R1 for models that incorporated both the jet fans (including the rotating blades) and the tunnel in a single CFD run. Turbulence effects were simulated using the k-ω shear stress transport model of Menter (1994), in order to accurately capture aerodynamic separation and reattachment effects. A single rotating blade was modelled within the jet fan, with periodic boundary conditions set at the end faces of the rotating domain to simulate a full ring of blades. Steady-state calculations were undertaken. The computational mesh was refined with prism layers on all solid surfaces, with y^+ values less than 25 on blade surfaces, and less than 60 on the internal jet fan surfaces. Tarada *et al* (2022) reported that calculated bench thrust values were within 3% of measurements, and calculated in-tunnel thrust values were within 2% of measurements.

<u>Selected configurations</u>

The following configurations of jet fans and installation locations were selected for this study:

A rectangular tunnel with 9 m width and 6.6 m height and which corresponds to 2-lane road tunnel with a hard shoulder. Fans were placed in the vicinity of a corner (Figure 9) or under a soffit (Figure 10).

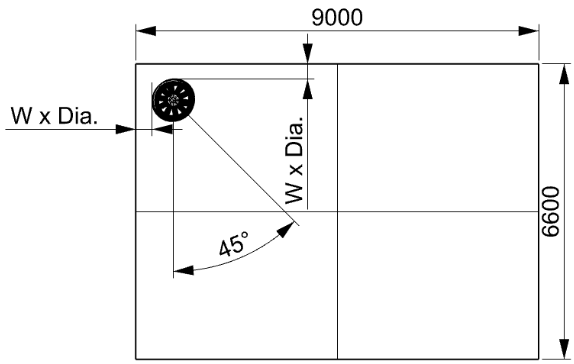


Figure 9: Tunnel cross-section, with a MoJet in a corner (all dimensions in mm)

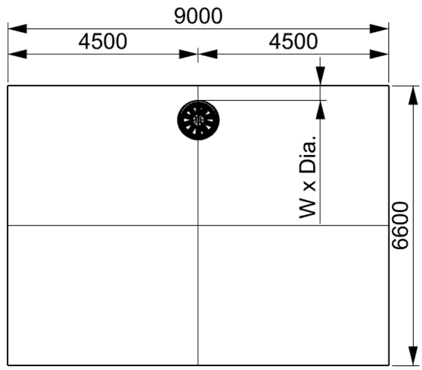


Figure 10: Tunnel cross-section, with a fan below the soffit (all dimensions in mm)

(1) Three sets of clearances between the outer silencer and the wall (or soffit) were simulated, denoted by “POS 01” (only 50 mm clearance), “POS 03” (0.3 × fan diameter) and “POS 05” (0.5 × fan diameter), where the fan diameter was either 710 or 1250 mm. Table 1 summarises the clearances adopted in this study.

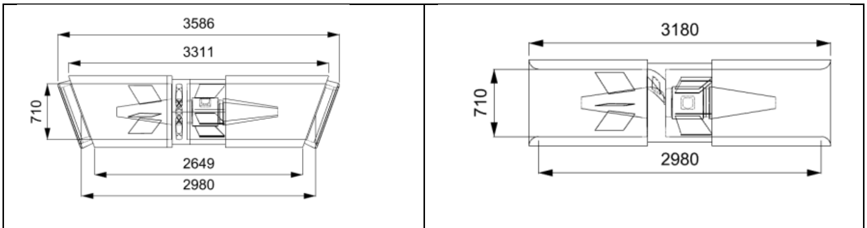
	“POS 01” clearance (mm)	“POS 03” clearance (mm)	“POS 05” clearance (mm)
710 mm fan	50	213	355
1250 mm fan	50	375	625

Table 1: Clearances employed between jet fans and tunnel

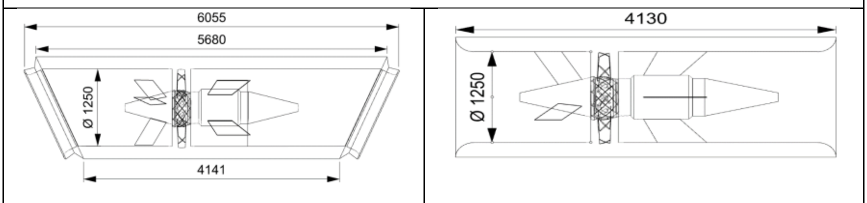
(2) Two jet fan diameters were selected for the study: 1250 mm and 710 mm (Table 2). The range encompassed by these diameters corresponds to the majority of jet fan sizes currently installed in tunnels worldwide. The bench thrust values for the MoJet were approximately the same as those for conventional jet fans, when the vector sum of both the vertical and horizontal components of thrust were considered.

Jet fan internal diameter (mm)	Number of blades	Blade pitch angle	Bench thrust (N)
710	10	34.6°	782
1250	10	32°	1695

Table 2: Jet fans considered in this study



710 mm diameter MoJet (left) and conventional jet fan (right) dimensions



1250 mm diameter MoJet (left) and conventional jet fan (right) dimensions

Figure 11: Jet fan dimension (all dimensions in mm)

(3) In order to model the potential aerodynamic interactions between the jet fans, five fans were modelled in each CFD run, with longitudinal spacings set at approximately 5, 10 and 15 tunnel hydraulic diameters (40 m, 80 m and 120m). At least one of these five jet fans, namely the third jet fan in the downstream direction, was defined to be a "master" fan (where the rotating blades were modelled), with all other fans being "slaves" (in which the aerodynamic and thermodynamic properties at the mixing planes upstream and downstream of the rotating blades are regularly copied from the master fans during the simulations). Sensitivity tests were undertaken to determine whether activating a second master fan (namely the first jet fan in the downstream direction) would affect installation factor results. These calculations indicated that the installation factor results were not sensitive to the addition of another master fan.

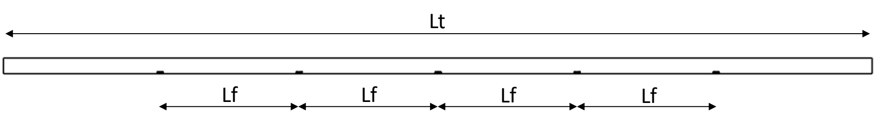


Figure 12: Tunnel lengths and fan spacing

Description	Case label	Tunnel length (Lt) (m)	Fan spacing (Lf) (m)
Fans spaced 5 times the tunnel hydraulic diameter	D05	300	40
Fans spaced 10 times the tunnel hydraulic diameter	D10	500	80
Fans spaced 15 times the tunnel hydraulic diameter	D15	720	120

Table 3: Jet fan longitudinal spacing

(4) The tunnel air velocity was varied between 1 m/s to 6 m/s, which is a typical range for tunnel operation.

(5) For MoJet calculations within a corner, the orientation of the MoJet silencer is assumed to be directed at 45° to the vertical, please refer to Figure 9.

Other parameters employed for this study

A sandgrain roughness height of 8 mm was applied to the tunnel surfaces, in order to produce a Darcy friction factor of approximately 0.02, which is typical for road tunnels.

5. MESH GENERATION

The CFD meshes required for this study was generated using Fluent's own mesh generator. This was configured to deliver polyhedral cells for the volume mesh, and prism layers near all solid surfaces to resolve near-wall boundary layers. The discharged jets were resolved through grid refinement cones within the tunnel, in order to minimise numerical diffusion. Examples of mesh densities are provided in Figure 13 to Figure 15.

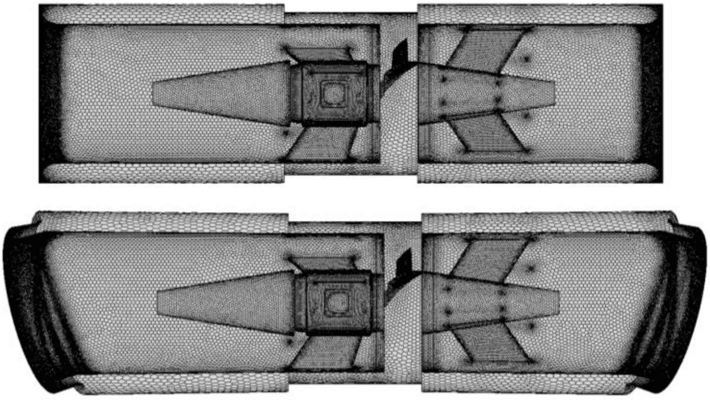


Figure 13: Surface mesh for 710 mm jet fans (above: conventional, below: MoJet)

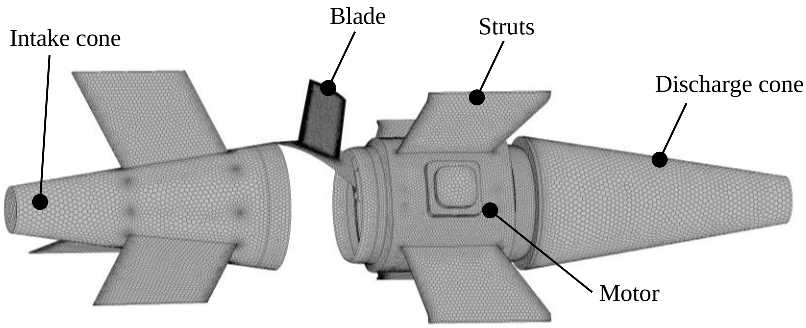


Figure 14: Surface mesh the internal parts of a jet fan

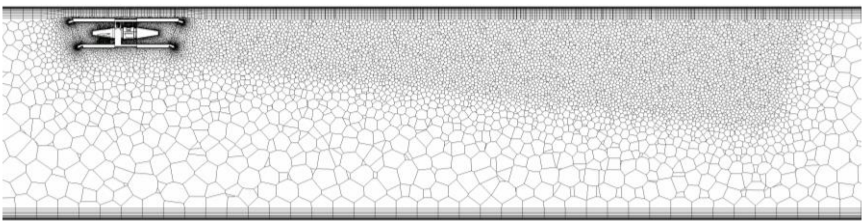


Figure 15: Volume mesh for 710 mm MoJet underneath the soffit at POS 05, showing grid refinement in the discharge jet zone

The number of computational cells employed varied from approximately 14 million for tunnel cases with conventional jet fans to 30 million for tunnel cases with MoJets. The difference in cell count was due to the need to refine the mesh in the areas of the bellmouths, in order to capture areas of flow separation and reattachment within the MoJet.

6. INSTALLATION FACTOR CALCULATIONS

The installation factors implied by the CFD calculations were estimated using the following formula (Tarada *et al,* 2022):

$$\eta_i = (A_T \Delta P_s + \Delta M_x + S_x)/\{T_B(1 - \frac{V_T}{V_j})\} \qquad \text{Equation (2)}$$

where

$A_T \Delta P_s$ = Longitudinal pressure drop along the tunnel [N]

ΔM_x = Increase in the longitudinal component of momentum across the tunnel domain [N]

S_x = Shear stress acting on the tunnel surfaces in the longitudinal direction, for the case of an equivalent tunnel without jet fans, but with the same longitudinal air velocity [N]

T_B = Jet fan bench thrust for the fans present in the tunnel domain [N]

Equation (2) was derived on the basis of a momentum balance across the tunnel domain. In a steady-state calculation. the effective thrust generated by the jet fans is equivalent to the differences in pressure-induced forces across the two tunnel portals, plus the increase in the longitudinal flow momentum, plus the "effective" part of the tunnel shear force (i.e.

ignoring the additional shear forces due to the attachment of the jets onto the tunnel surfaces).

7. CFD RESULTS

Coanda effect and jet deflection

The CFD results for the 1250 mm jet fans installed at "POS 1" underneath a soffit are indicative of the Coanda effect and jet deflection. Figure 16 shows the contours of velocity downstream of a conventional jet fan. The jet is deflected slightly upwards due to the Coanda effect and attaches to the soffit, causing high shear and the loss of in-tunnel thrust. The same pattern is repeated for all the three tunnel air velocities considered (1, 3 and 6 m/s). Please note that only the upper part of the tunnel is depicted in Figure 16, in order to focus on the jet pattern.

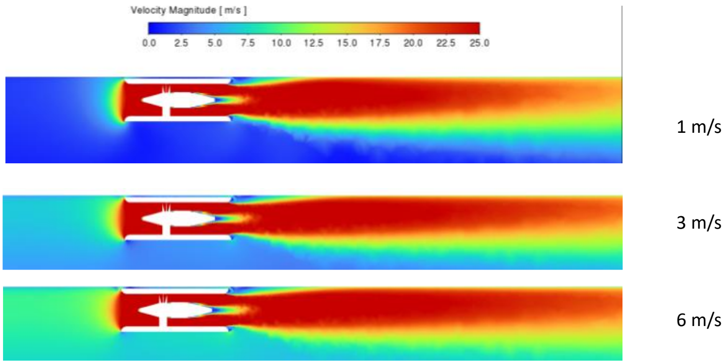


Figure 16: Velocity contours under a soffit with a conventional 1250 mm jet fan at POS 1, at various tunnel air velocities

Figure 17 shows the equivalent velocity contours with a 1250 mm MoJet. The discharge jet is seen to be deflected downwards, reducing the aerodynamic shear at the soffit and enhancing the in-tunnel thrust. Please note that only the upper part of the tunnel is depicted in Figure 17.

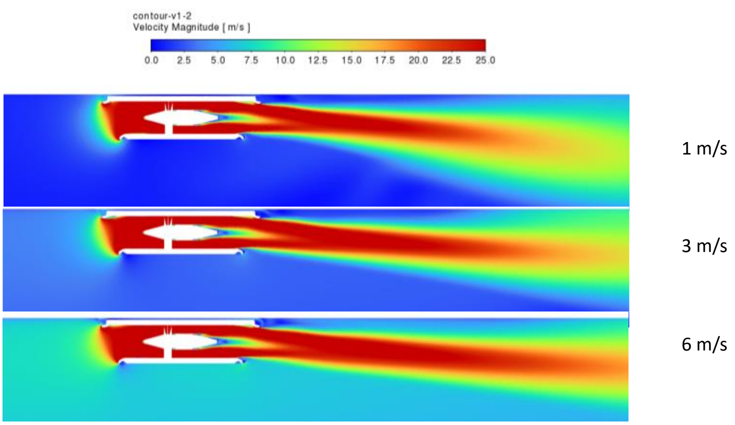


Figure 17: Velocity contours under a soffit with a 1250 mm MoJet at POS 01 with various tunnel air velocities

Installation factors for 1250 mm fans at 80 m longitudinal spacing

Figure 18 shows the calculated jet fan installation factors for 1250 mm jet fans at 80 m longitudinal spacing, for corner-mounted fans. Considering the MoJet results for "POS 03": these are significantly higher than the equivalent results for conventional jet fans (around 27% higher in-tunnel thrust at 3 m/s tunnel air velocity). The MoJet installation factors reduce with increasing tunnel air velocity, up to 3 m/s. This is due to the elongation of the "friction patch" between the jet and the corner wall and soffit with increasing tunnel air velocity, and is consistent with the findings of other researchers (e.g. Beyer *et al*, 2016). However, the MoJet installation factors start rising beyond 3 m/s tunnel air velocity, which was unexpected. Analysis of the CFD results indicated that this was due to enhanced mixing between the jet and the tunnel air at the higher velocities, which reduced the length of the "friction patch". Much of the benefit of the MoJet above a conventional jet fan is lost if the fans are installed right up against a corner (i.e. at "POS 01").

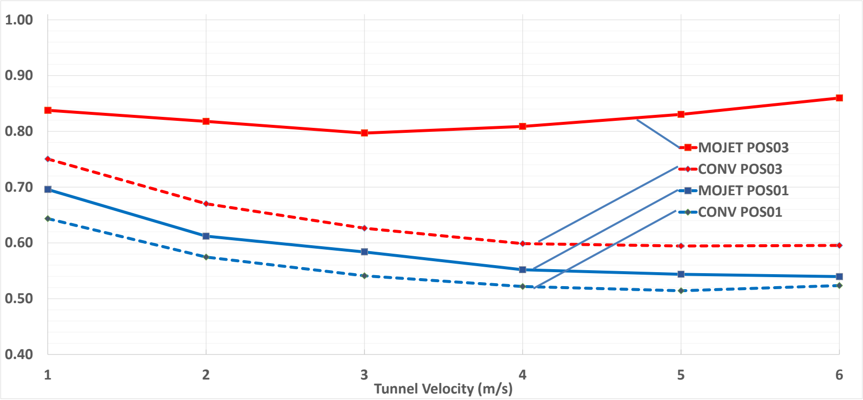


Figure 18: Installation factor for corner-mounted 1.25m diameter jet fans at 80m spacing

The installation factor results for soffit-mounted fans are presented in Figure 19. They are all higher than those for the equivalent corner-mounted fans, because the discharge jet can only attach to one surface, namely to the soffit. The MoJet shows a significant advantage compared to conventional jet fans, even when installed with a very small clearance to the soffit ("POS 01").

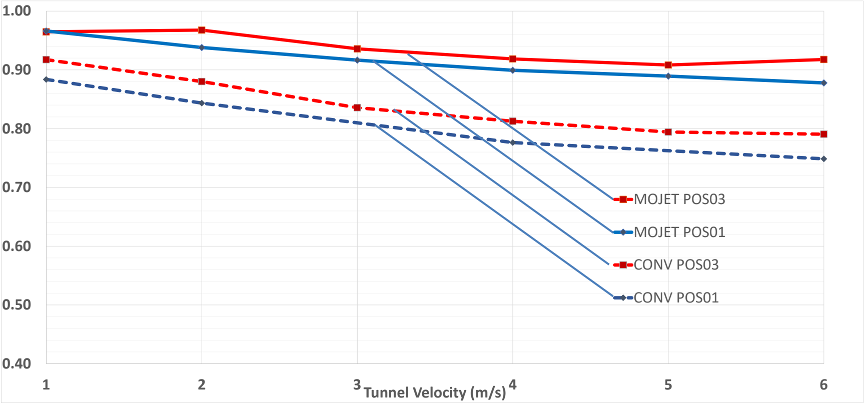


Figure 19: Installation factor for soffit-mounted 1.25 m diameter jet fans at 80m spacing

Installation factors for 710 mm fans at 80 m longitudinal spacing

We repeated some of our CFD calculations with 710 mm jet fans, in order to establish whether a reduction jet fan diameter would lead to reduced installation factors, as reported by Beyer *et al* (2016). Figure 20 shows the installation factors 710 mm diameter corner-mounted fans with varying tunnel velocities at POS 05. The results confirm Beyer *et al*'s results, when Figure 20 is compared to the results in Figure 18 and accounting for the differences in the clearances to the corner.

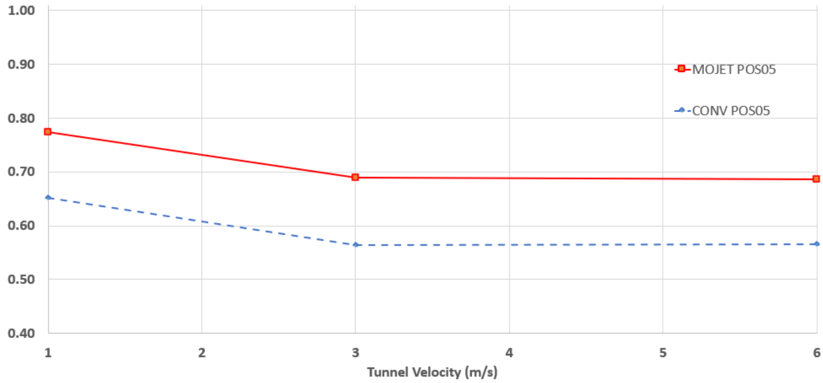


Figure 20: Installation factor for 710 mm diameter corner-mounted fans at 80m spacing with varying tunnel velocities (at POS 05)

Figure 21 shows the installation factors for 710 mm diameter soffit-mounted fans with varying tunnel velocities at POS 01 (50 mm clearance) and POS 05 (355 mm clearance). Again, the installation factors with shaped silencers are consistently better than those for conventional jet fans, for both clearances and for the whole range of tunnel air velocities. The results for POS 05 are broadly similar to those for the 1250 mm soffit-mounted fans at POS 03 (375 mm clearance). The absolute value of the clearance, rather than the clearance ratio or the jet fan diameter, appears to be the determining factor for determining the installation factor for soffit-mounted jet fans – although more research is required to confirm this tentative conclusion.

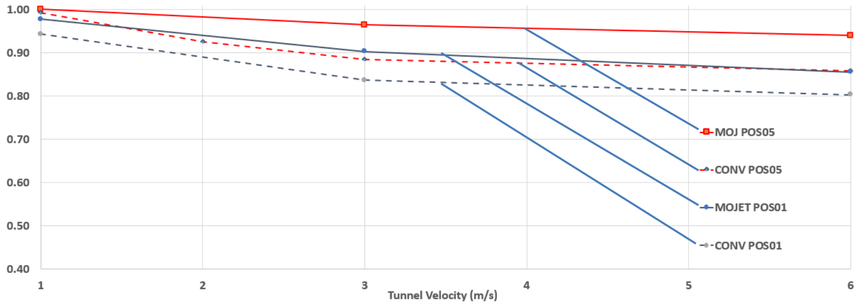


Figure 21: Installation factor for 710 mm diameter soffit-mounted fans at 80m spacing with varying tunnel velocities (at POS 05)

Effect of longitudinal fan spacing

Figure 22 shows the effect of longitudinal spacing on the 1250 mm diameter corner-mounted fans at POS 03, at 3 m/s tunnel air velocity. It is clear that the guideline of "10 tunnel hydraulic diameters" usually applied to space conventional jet fans leads to relatively low in-tunnel thrust for this scenario. This is due to the unloading effect, whereby downstream jet fans ingest high-velocity air issued by upstream jet fans. This effect is also present with the MoJet, but to a lesser extent than with conventional jet fans.

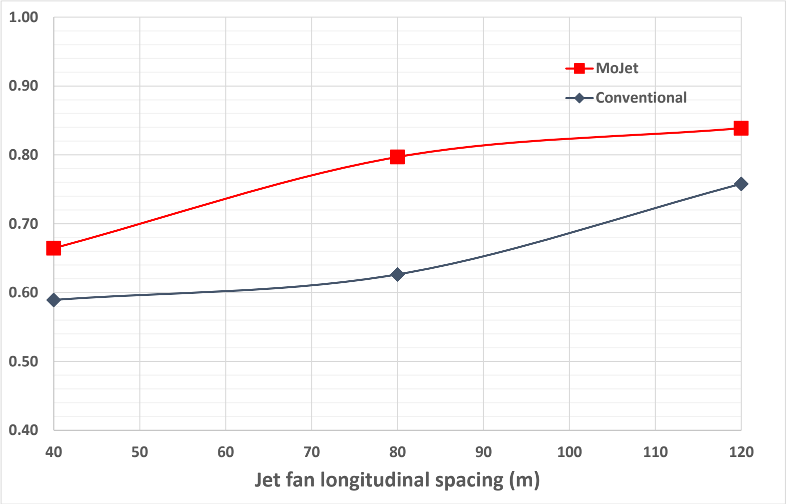


Figure 22: Installation factor for 1250 mm diameter corner-mounted fans at POS 03 with varying longitudinal spacing (at 3 m/s tunnel velocity)

8. DISCUSSION AND CONCLUSIONS

MoJet installation factors were calculated to be consistently higher than those of equivalent conventional jet fans. Some of the MoJet CFD cases have indicated results with installation factors that are equal to, or close to unity. This shows that, contrary to previous recommendations such as those provided by Costeris (1991), there is no need to limit the effective jet fan thrust to its horizontal component – rather, the total thrust should be considered, as long as the discharged jet does not adhere to the tunnel floor or to other surfaces (Tarada and Else, 2018). The reason for this is based on Newton's Third Law: the flow being discharged from a shaped silencer experiences a downward force exerted by the bellmouth, but this is counteracted by an equal and opposite force exerted by the neighbouring streamlines in the tunnel (and ultimately by the tunnel floor), which act to push the discharged flow back towards the horizontal direction.

The use of 3D CFD provides an opportunity to accurately calculate the in-tunnel thrust generated by jet fans, as an alternative to employing previous studies which used unrepresentative experimental conditions. The authors intend to continue their research and to generate generally-applicable jet fan installation factor correlations for a wide range of applications.

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