JET FAN INSTALLATION FACTOR CORRELATIONS FOR CONVENTIONAL JET FANS AND MOJETS

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ABSTRACT

This paper presents the results of nearly 1,000 CFD calculations undertaken with two jet fan diameters, two jet fan installations, two different surface roughness values, for a range of tunnel velocities, with various jet fan spacings, with varying clearances between the jet fan and the tunnel surface and with two types of jet fans (conventional and MoJet). The CFD calculations were undertaken with the ANSYS Fluent code and were validated by reference to the full-scale tunnel measurements reported by Tarada et al [5]. The calculations modelled a 2-lane road tunnel with hard shoulder - 9.6 m wide, 6 m high and 500 m long, along with its associated jet fans (including their rotating blades). Cell counts for each CFD simulation ranged from 20 to 35 million, using polyhedral and prism cells for maximum accuracy.

The results of our CFD calculations were correlated in the form of mathematical expressions, which account for each of the considered influencing parameters (jet fan diameter, type of installation, surface friction factor, tunnel velocity, jet fan spacing and clearance, and jet fan type). We report on the open provision of these correlations via web tools, to facilitate their use by designers and researchers in this field.

Keywords: Jet fan, thrust, installation factor, CFD, measurements, correlations

1. INTRODUCTION

Following PIARC [1], the jet fan installation factor η_i is used to calculate the in-tunnel value of thrust (T) using the following equation:

$$T = \eta_i \rho A_j v_j (v_j - v_t) \quad \text{(Equation 1)}$$

where A_j is the cross section of the jet fan, 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 (Meidinger [2] and Truckenbrodt [3]). Although Equation 1 was developed for conventional jet fans, the same formulation can be used for jet fans with shaped silencers (MoJets), 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).

As previously reported by Tarada and Bertacche [6], previous correlations for jet fan installation factors suffer from a range of limitations, including being based on low model-scale Reynolds numbers, the lack of discharge swirl in the physical tests and their applicability to only a single jet fan, rather than relating to multiple jet fans in a series. This study was undertaken to address these limitations, and to provide a more reliable set of jet fan installation factor correlations for designers.

2. CFD METHODOLOGY AND VERIFICATION

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 [5]. 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 [4], in order to accurately capture aerodynamic separation and reattachment effects. The computational mesh comprised polyhedral cells 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. Cell counts for each CFD simulation ranged from 20 to 35 million, with higher cell counts being required to resolve the aerodynamics around bellmouths for MoJet simulations. Tarada et al [5] reported that calculated bench thrust values were within 3% of measurements, and calculated in-tunnel thrust values were within 2% of measurements.

For each CFD run, three jet fans separated by a defined longitudinal spacing were simulated within the tunnel. In order to economise on mesh sizes and run times, the last jet fan (in the downstream direction) was set up as a "master" jet fan, while the other two were defined to be "slave" jet fans. The flow, pressure and turbulence profiles in the upstream and downstream mixing planes either side of the rotor were regularly copied from the master to the slave jet fans during the CFD runs. Within the master jet fan, a single rotating blade was modelled, 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. Jet fan installation factors were post-processed from the CFD results based on the procedure described in Tarada et al [5].

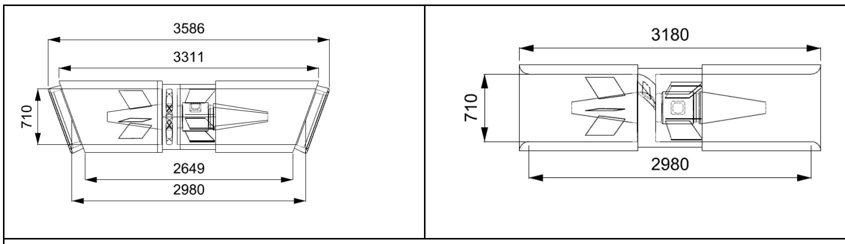
3. TUNNEL AND JET FAN GEOMETRIES

The tunnel and jet fan geometries considered in this study were the same as those reported by Tarada and Bertacche [6], and are briefly reproduced below for completeness. A description of the shape and function of MoJet silencers is provided by Tarada et al [7].

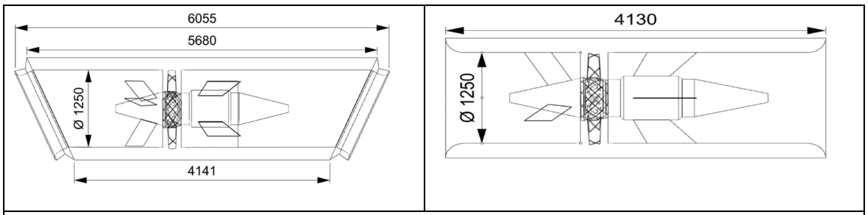
Two jet fan diameters were selected for the study: 1250 mm and 710 mm (Table 1). The range encompassed by these diameters corresponds to the majority of jet fan sizes currently installed in tunnels worldwide. The bench thrust values for the MoJet were approximately the same as those for conventional jet fans, when the vector sum of both the vertical and horizontal components of thrust are considered.

Table 1: Jet fans considered in this study

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



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



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

Figure 1: Jet fan dimension (all dimensions in mm)

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 or under a soffit (Figure 2).

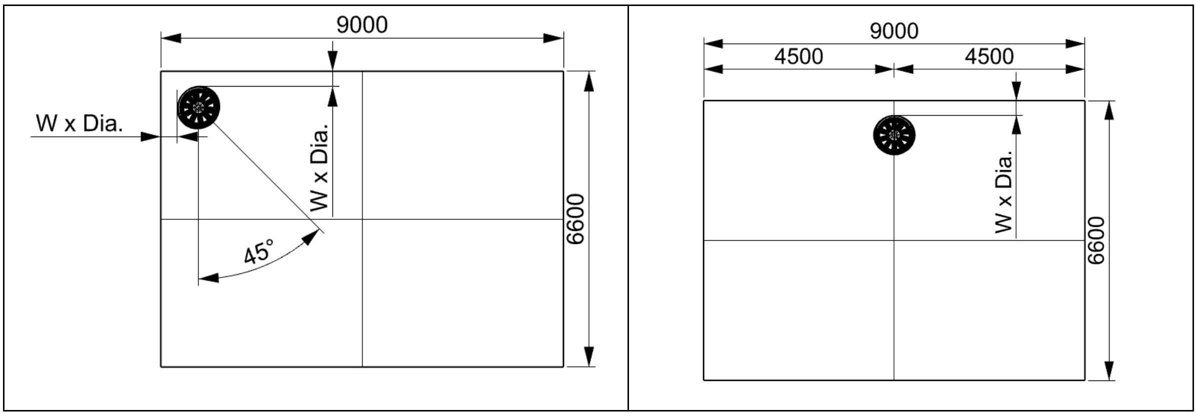


Figure 2: Tunnel cross-section, with a fan at a corner (left) and below the soffit (right) - all dimensions in mm

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 × 1250 mm fan diameter) and "POS 05" (0.5 × 1250 mm fan diameter). Table 2 summarises the clearances adopted in this study.

Table 2: Clearances employed between jet fans and tunnel

	"POS 01" clearance (mm)	"POS 03" clearance (mm)	"POS 05" clearance (mm)
710 mm fan	50	375	625
1250 mm fan	50	375	625

In order to model the potential aerodynamic interactions between the jet fans, three 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). Two sand-grain roughness heights were applied to the tunnel surfaces in our study: 8 mm which produces a Darcy friction factor of 0.02140, and 80 mm roughness height, which produces a Darcy friction factor of 0.02838. Tunnel air velocities between 1 to 6 m/s were simulated.

4. CFD RESULTS

A selection of results of our CFD analyses are presented below. These indicate the behaviour of the installation factor with the major variables considered in our study, as well as their predicted trends based upon our proposed correlations (which are presented in section 5). The symbols within the plots below indicate our CFD results, while the lines represent our correlations. It can be seen that there is generally a close correspondence between the CFD results and the correlations.

We observed that the general trend is for the installation factors to reduce with increasing tunnel velocity (Figure 3), which is due to the stretching of the "friction patch" downstream of the jet fans, on the neighbouring tunnel surfaces. However, some recovery of the installation factor was observed for the highest velocities, particularly with the MoJet, due to more intensive mixing of the jet with the tunnel air.

As can be reasonably expected, increasing the clearance between the jet fans and the tunnel surfaces leads to improvements in the installation factor (Figure 4), although the trend is influenced by the jet fan diameter – smaller diameter conventional jet fans tend to have smaller installation factors. This is possibly due to the effects of the tunnel boundary layer and due to the higher discharge velocities associated with smaller tunnel jet fans driven by two-pole motors, which cause higher shear on the neighbouring tunnel surfaces.

Figure 5 demonstrates the "unloading effect" of the loss of thrust when jet fans are installed at short longitudinal spacing, as previously reported by Costeris [8]. In particular, Figure 5 shows that the conventional rule of designing conventional jet fans with ten hydraulic diameter spacing appears to deliver significantly lower jet fan installation factors than would be expected for a single jet fan. Although the mass flow through downstream jet fans is slightly increased through the ingestion of jets, a significant proportion of the upstream jets may be captured through such ingestion, leaving a smaller proportion of longitudinal momentum to exchange with the tunnel air. MoJets are less sensitive to jet fan spacing, due to the deflection of the jet away from the downstream fans.

Figure 6 shows a trend of reducing installation factors with increasing tunnel friction factors for conventional jet fans, due to the increased friction between the jet and the tunnel surfaces. MoJets are less sensitive to changes in tunnel friction factors.

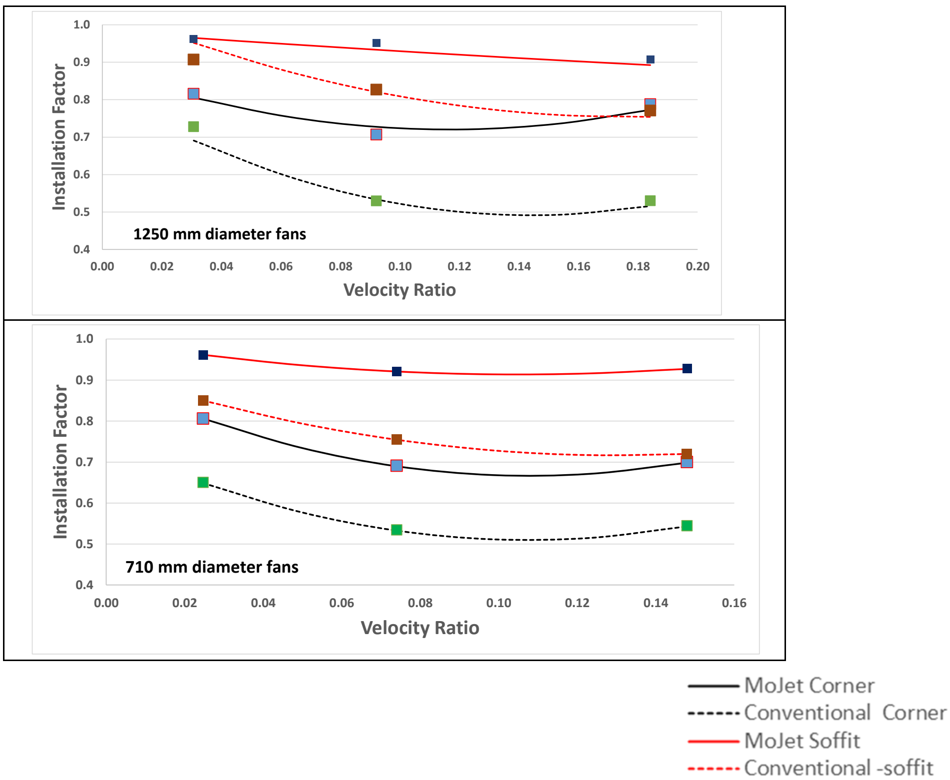


Figure 3: Variation of installation factor with velocity ratio for the 1250 mm fan (left) and the 710 mm fan (right), for 3 m/s tunnel air velocity and 8 mm tunnel surface sand-grain roughness

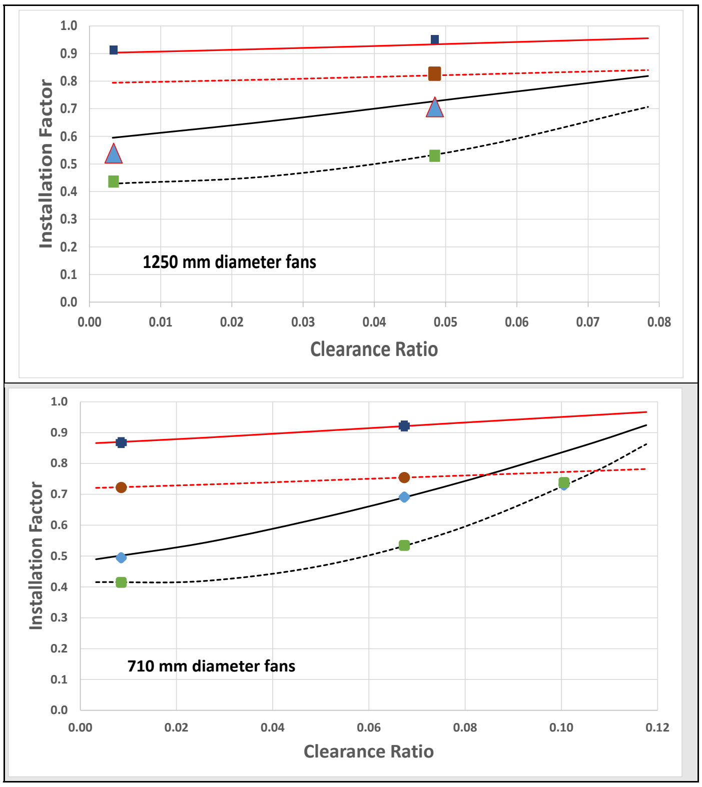


Figure 4: Variation of installation factor with clearance ratio for the 1250 mm fan (left) and the 710 mm fan (right), for 3 m/s tunnel air velocity and 8 mm tunnel surface sand-grain roughness

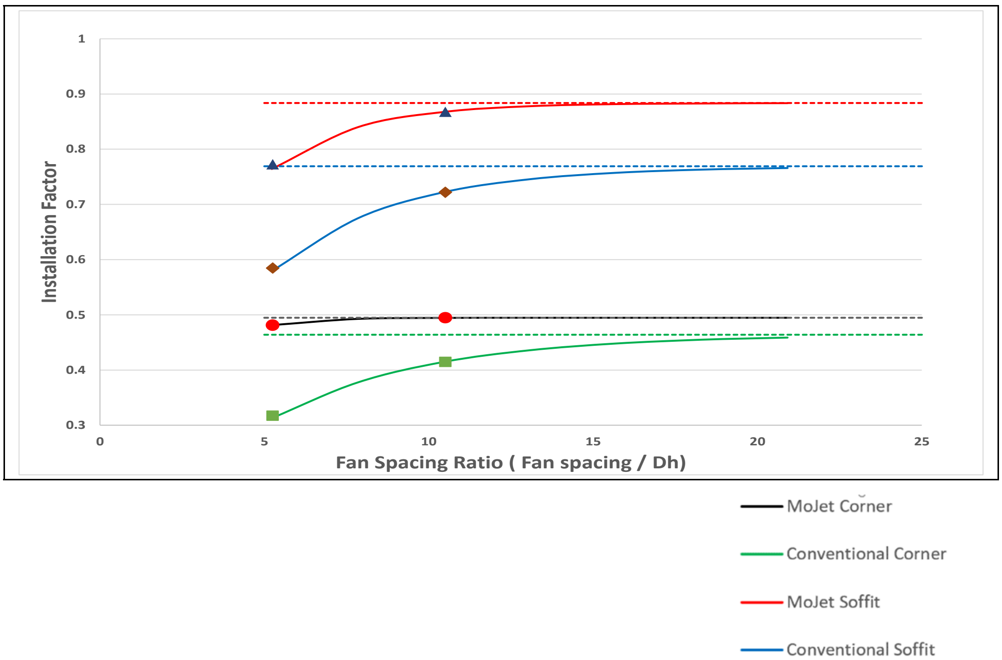


Figure 5: Variation of installation factor with fan spacing ratio for 710mm Fan at 3m/s, 8mm sand-grain roughness, POS 01 for soffit and POS 03 for corner

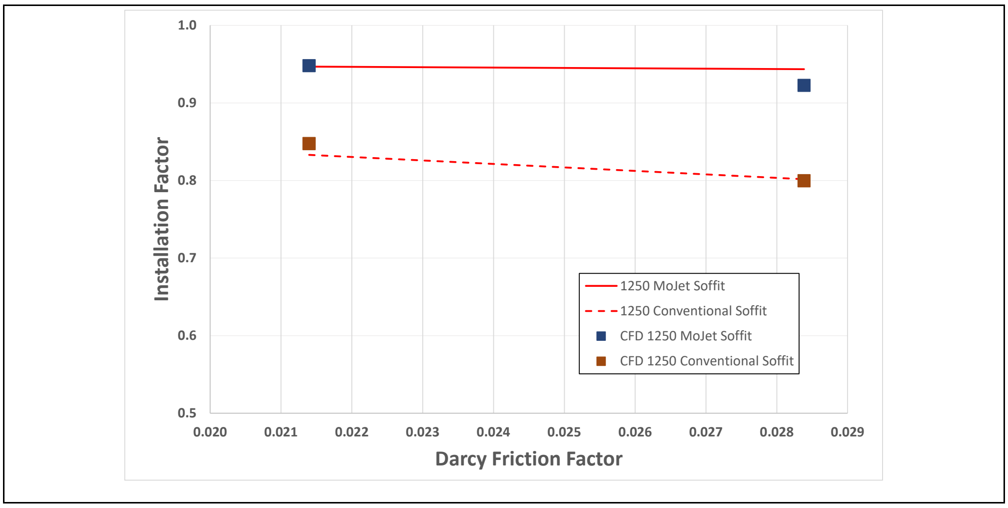


Figure 6: Variation of installation factor with Darcy friction factor ratio for the 1250 mm fan at POS 03 for 3 m/s tunnel air velocity

5. INSTALLATION FACTOR CORRELATIONS

Definitions

$v_r = \frac{v_t}{v_j}$ = velocity ratio between tunnel velocity (v_t) and jet velocity (v_j)

$$c_{fr} = \text{fan clearance ratio} = \frac{(clearance\ to\ silencer + silencer\ thickness)}{Tunnel\ hydraulic\ diameter\ (D_H)}$$

$f_{dr} = \frac{D_f}{D_H}$ = fan diameter ratio

D_f = fan diameter

f_s = fan spacing correction ratio

f_f = friction Factor correction ratio

F_{fcr1}, F_{fcr2} *and* F_{fcr3} = fan diameter correction ratios

F_f = Darcy friction factor for the tunnel

Installation Factor Calculation

Installation Factor $\eta_i = (a_{v1}\, v_r^2 + b_{v1}\, v_r + c_{v1})f_s\, f_f$

The velocity coefficients a_{v1}, b_{v1} *and* c_{v1} are corrected based on the fan diameter and on the clearance ratio.

Calculation of the velocity coefficients

$$\begin{pmatrix} a_{v1} \\ b_{v1} \\ c_{v1} \end{pmatrix} = \begin{pmatrix} m_{a1} & q_{a1} \\ m_{b1} & q_{b1} \\ m_{c1} & q_{c1} \end{pmatrix} \begin{pmatrix} f_{dr} \\ 1 \end{pmatrix}$$

f_{dr} = correction for fan diameter ratio (D_f/D_H)

$$\begin{pmatrix} a_{1lfr} \\ b_{1\,lfr} \\ c_{\,1lfr} \end{pmatrix} = \begin{pmatrix} a_a & b_a & c_a \\ a_b & b_b & c_b \\ a_c & b_c & c_c \end{pmatrix} \begin{pmatrix} c_{fr}^2 \\ c_{fr} \\ 1 \end{pmatrix}$$ for the 710 mm fan diameter

$$\begin{pmatrix} a_{1ufr} \\ b_{1ufr} \\ c_{1ufr} \end{pmatrix} = \begin{pmatrix} a_{1lfr} \\ b_{1lfr} \\ c_{1lfr} \end{pmatrix} \begin{pmatrix} F_{fcr1} \\ F_{fcr2} \\ F_{fcr3} \end{pmatrix} \text{for the 1250 mm fan diameter}$$

$$m_{a1} = \frac{a_{1ufr} - a_{1lfr}}{0.0706} \qquad q_{a1} = a_{1lfr} - 0.0928 m_{a1}$$

$$m_{b1} = \frac{b_{1ufr} - b_{1lfr}}{0.0706} \qquad q_{b1} = b_{1lfr} - 0.0928 m_{b1}$$

$$m_{c1} = \frac{c_{1ufr} - c_{1lfr}}{0.0706} \qquad q_{c1} = c_{1lfr} - 0.0928 m_{c1}$$

Fan spacing correction ratio

R_{fs} =Fan spacing ratio for a particular fan, which is the ratio of the installation factor at user fan spacing divided by the installation factor at 80m fan spacing (approximately 10 times the hydraulic diameter of our simulated tunnel) for a reference velocity ratio of 0.092 and a reference clearance ratio of 0.081.

$$R_{fs} = \frac{1 - e^{(-\delta F_{SP})}}{1 - e^{(-\delta 80)}}$$

δ = fans spacing corelation factor that depends on the type of fan and installation position
F_{SP} = fan spacing in metres

$$f_s = \frac{R_{fs1250} - R_{fs710}}{0.0706} f_{dr} + R_{fs710} - 1.3144(R_{fs1250} - R_{fs710})$$

The subscript in R_{fs} denotes the diameter of the reference fans used in the correlation.

Friction Factor Correction Ratio

Corner Position

For MoJet: $f_f = -8.37922\, F_f + 1.17929$

For Conventional Jet Fan: $f_f = -20.70549\, F_f + 1.4430$

Soffit Position

For MoJet: $f_f = -0.52625\, F_f + 1.01126$

For Conventional Jet Fan: $f_f = -5.40106 F_f + 1.11556$

Variation of Velocity Coefficients vs Clearance

MoJet Corner

$$\begin{pmatrix} a_a & b_a & c_a \\ a_b & b_b & c_b \\ a_c & b_c & c_c \end{pmatrix} = \begin{pmatrix} -1605.3000 & 122.9000 & 20.4740 \\ 777.4700 & -72.8750 & -3.4844 \\ -36.4110 & 6.7807 & 0.5900 \end{pmatrix}$$

Conventional Jet Fan Corner

$$\begin{pmatrix} a_a & b_a & c_a \\ a_b & b_b & c_b \\ a_c & b_c & c_c \end{pmatrix} = \begin{pmatrix} 996.8000 & -128.6200 & 24.1150 \\ -167.5500 & 14.6600 & -4.4434 \\ 48.6440 & -2.6283 & 0.6406 \end{pmatrix}$$

MoJet Soffit

$$\begin{pmatrix} a_a & b_a & c_a \\ a_b & b_b & c_b \\ a_c & b_c & c_c \end{pmatrix} = \begin{pmatrix} 0 & -8.7932 & 8.0717 \\ 0 & 5.6151 & -1.9977 \\ 0 & 0.5398 & 0.9516 \end{pmatrix}$$

Conventional Jet Fan Soffit

$$\begin{pmatrix} a_a & b_a & c_a \\ a_b & b_b & c_b \\ a_c & b_c & c_c \end{pmatrix} = \begin{pmatrix} 0 & 0.7277 & 11.8340 \\ 0 & 1.8226 & -3.2575 \\ 0 & 0.4078 & 0.8866 \end{pmatrix}$$

Fan Diameter Correction Ratios

MoJet Corner

$$\begin{pmatrix} F_{fcr1} \\ F_{fcr2} \\ F_{fcr3} \end{pmatrix} = \begin{pmatrix} 0.55793 \\ 0.58652 \\ 0.98222 \end{pmatrix}$$

MoJet Soffit

$$\begin{pmatrix} F_{fcr1} \\ F_{fcr2} \\ F_{fcr3} \end{pmatrix} = \begin{pmatrix} 0.05719 \\ 0.35816 \\ 0.98995 \end{pmatrix}$$

Conventional Corner

$$\begin{pmatrix} F_{fcr1} \\ F_{fcr2} \\ F_{fcr3} \end{pmatrix} = \begin{pmatrix} 0.77196 \\ 1.04373 \\ 1.13734 \end{pmatrix}$$

Conventional Soffit

$$\begin{pmatrix} F_{fcr1} \\ F_{fcr2} \\ F_{fcr3} \end{pmatrix} = \begin{pmatrix} 0.77196 \\ 1.04373 \\ 1.13734 \end{pmatrix}$$

Fan Spacing Correction Factor Data

For Corner Position

Correlation Variable	1250 Fan Diameter		710 Fan Diameter	
	MoJet	Conventional	MoJet	Conventional
δ	0.033	0.02	0.09	0.028

For Soffit Position

Correlation Variable	1250 Fan Diameter		710 Fan Diameter	
	MoJet	Conventional	MoJet	Conventional
δ	0.09	0.04	0.05	0.035

6. SUMMARY AND CONCLUSION

Our 3D CFD calculations have indicated the variation of jet fan installation factor with variables including tunnel velocity, clearance to tunnel surfaces, spacing between jet fans, tunnel friction factor and jet fan diameter. We have developed correlations of our CFD results for both conventional jet fans and MoJets. The latter type of fans are designed to deflect the flow away from the bounding tunnel surfaces and enhance the installation factor, without compromising the jet fan bench thrust. To facilitate the use of our correlations, these have been implemented via Excel via a website [9] and independently checked via Matlab. The correlations provide a much better basis for the estimation of jet fan installation factors than previous guidance (Ref. [6]), although engineering judgment and caution are always advised in the design of longitudinal tunnel ventilation via jet fans. The current paper does not address installation factors for banks of jet fans installed at the same tunnel chainage, nor does it address arched tunnel soffits. Further full-scale tunnel testing of our CFD predictions and correlations, in particular related to the effect of jet fan spacing, banks of jet fans and arched tunnel soffits, are currently underway and will be reported in future publications.

7. REFERENCES

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