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MEASUREMENTS AND CFD CALCULATIONS WITH A MOJET AND A CONVENTIONAL JET FAN

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ABSTRACT

A series of measurements were undertaken with a 1.25m internal diameter, fully reversible jet fan in a factory and in the Rendel Street branch of the Mersey Queensway tunnel in Birkenhead, England. The jet fan was fitted with conventional and shaped (MoJet) silencers on both sides of the fan. The MoJet silencers were designed to deflect the airflow away from the tunnel soffit, in order to reduce the friction between the discharged jet and the soffit. The measurements showed an increase in the in-tunnel MoJet thrust of nearly 30%, compared to the conventional jet fan. The power consumption figures of the MoJet and the conventional jet fan were approximately the same, both in factory tests and in the tunnel, within the defined uncertainty limits. The measured tunnel velocities were very close to the results of detailed 3D CFD calculations using ANSYS Fluent, which incorporated the full geometry of the jet fan (including the rotating blades) and the tunnel. Our measurements imply that the MoJet can be employed to reduce the number of jet fans and to decrease the power consumption required for longitudinal tunnel ventilation.

Keywords: Jet fan, MoJet, aerodynamics, thrust, power, CFD, Coanda, installation factor

1. INTRODUCTION

Jet fans are the most commonly used means of generating mechanical ventilation in tunnels. This is because of the relatively low capital costs associated with jet fans compared to alternative technologies (such as transverse or semi-transverse ventilation systems), since the alternatives generally require the construction of ventilation stations, shafts and ducts, and thereby entail higher construction costs. Despite the attraction of the jet fan solution from a capital cost perspective, the operating and maintenance costs of jet fans can be disproportionately high. This is partly due to inherent inefficiencies with conventional jet fans, with typical installations wasting over half the supplied electrical power, Ref. [1]. This inefficiency is due to two main reasons: aerodynamic friction between the jet discharged by jet fans and neighbouring tunnel surfaces, exacerbated by the Coanda effect, and the unloading of jet fans due to ingestion of high-speed jets from upstream jet fans, Ref. [2].

The MoJet is the latest innovation that has been implemented to improve the in-tunnel thrust delivered by jet fans and thereby to significantly improve their overall efficiency. MoJets incorporate shaped silencers, which direct the discharged flow away from adjacent tunnel surfaces, whilst avoiding flow separation at the intake silencer, Ref. [3]. Measurements with unidirectional MoJets installed within corners of a rectangular tunnel were shown to deliver 100% more in-tunnel thrust than conventional jet fans, Ref [4]. The study in this paper relates to aerodynamic measurements with a fully reversible MoJet and a conventional jet fan installed in a horseshoe-shaped tunnel.

The factory and tunnel measurements reported here were carried out by TLT-Turbo GmbH. The design of the MoJet and the 3D CFD calculations were undertaken by Mosen Ltd. Assistance with the aerodynamic measurements was provided by the Technical University at

Aachen. The tunnel measurements were undertaken with the kind permission of the public-sector transport provider for the Liverpool region, Merseytravel.

2. MOJET DESIGN

Our study was based upon a 1.25m internal diameter fan, with 10 blades mounted on the rotor. Two different sets of silencers were attached to this fan: conventional 1D (1.25m long) silencers and MoJet silencers with the same lower edge length as for the conventional jet fan. The outside diameter of the MoJet (1.65m) was the same as that of the conventional jet fan.

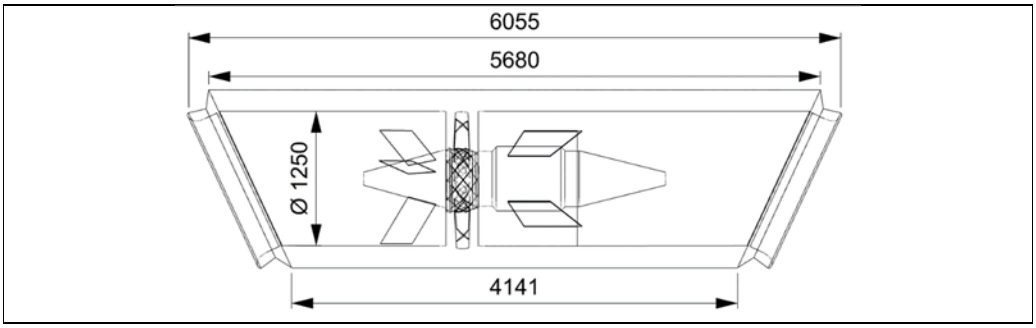

Figure 1: MoJet used in this study (dimensions in mm)

3. TUNNEL TEST ARRANGEMENTS

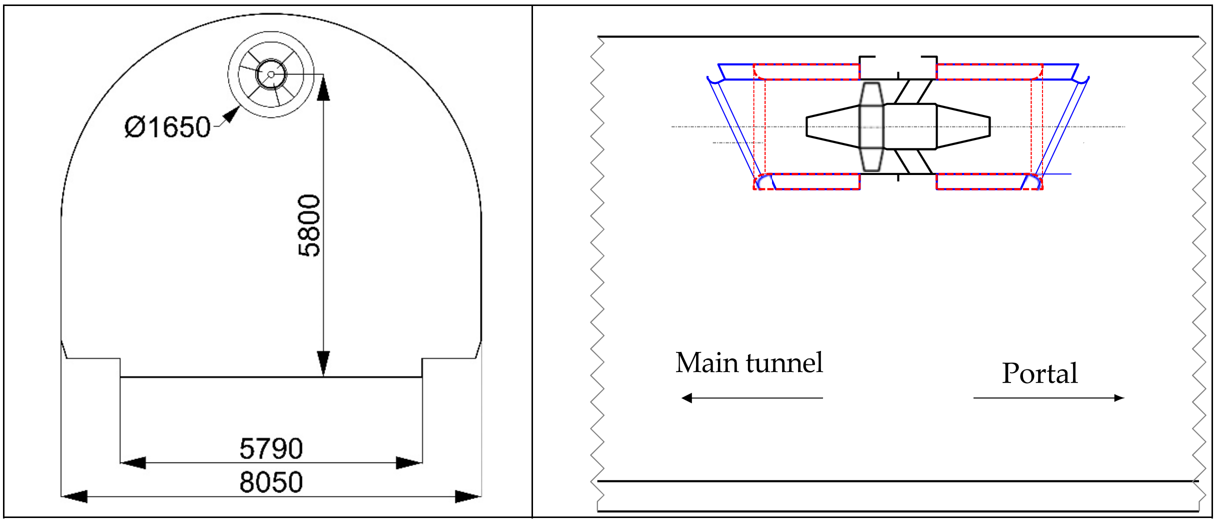

Figure 2: Locations of installed jet fan in tunnel (red=conventional jet fan, blue=MoJet), with dimensions in mm

The tests were undertaken in the disused branch Rendel Street branch of the Queensway Tunnel which connects the Birkenhead to Liverpool. The tunnel has two lanes, and has a horseshoe profile (figure 2). The total length of the branch tunnel is approximately 500 m. From the junction with the main tunnel, the branch tunnel runs straight for about 270 m. After that, there are two slight curves with intermediate lengths of about 100 m. After the second curve up to the portal, the tunnel is straight again. Furthermore, the tunnel has a slight incline along its entire length.

The jet fan was installed below the tunnel soffit, as shown in figure 2 and figure 3. The longitudinal axis of the fan was aligned parallel to the tunnel axis. The distance between the junction of the branch tunnel with the main tunnel to the location of the jet fan discharge was about 25 m. The clearance between the upper edge of the silencer and the tunnel ceiling was approximately 0.35 m.

Figure 3: MoJet installation in the Rendel Street branch tunnel

Velocity measurements were carried out at a distance of about 140 m downstream of the outlet from the jet fan over the entire tunnel cross–section. For that purpose, the velocities were measured at a total of 36 measuring points located at the tunnel cross section in accordance with the log-Tchebycheff distribution in BS EN ISO 5802:2008+A1:2015 (Ref. [5]). The locations of the velocity measuring points are shown in figure 4.

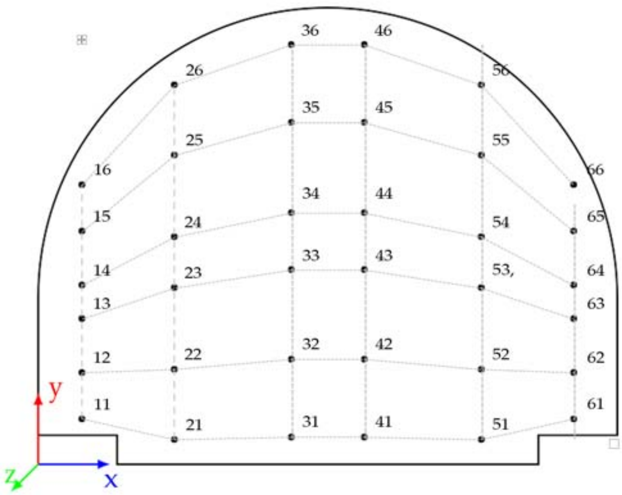

Figure 4: Distribution of the velocity measuring points over the tunnel cross section

Calibrated hot wire anemometers (Trotec BA30WP) were used, with Bluetooth connections to a tablet for data capture. Readings were taken every second for one minute at every measurement location, and then time-averaged.

Background airflow measurements were taken before and after each of the two tests (with the conventional jet fan and with the MoJet). Corrections were then applied to the air velocities in the following manner:

$$V_{effective}^2 = V_{av}^2 \pm V_{background}^2 \quad \text{(Equation 1)}$$

In practice, the corrections due to background velocities were found to be very small.

4. MEASUREMENT UNCERTAINTIES

The tunnel aerodynamic measurements were subject to systematic uncertainties (e.g. due to anemometer calibrations, direction of probes, finite number of measuring points) and to random measurement errors. We estimate that the random errors were within 3.5%, to 95% confidence in accordance with Ref. [5]. Most systematic uncertainties “cancelled out” due to comparative nature of exercise, since the same layout and measurement equipment was used for both the conventional jet fan and MoJet tests.

5. FACTORY TESTS

Prior to the tunnel tests, factory tests of the thrust and power consumption were undertaken for the conventional jet fan and the MoJet, in accordance with BS EN ISO 13350:2015 (Ref. [6]). Only the horizontal component of thrust was measured in these tests. The factory measurements are summarised in table 1 below. All measurements were referred to an air density of 1.2 kg/m^3.

Table 1: Factory measurements

	Horizontal component of thrust in forward direction (N)	**Electrical power consumption (kW)**
Conventional jet fan	2221	87.6
MoJet	2123	87.7

The thrust and electrical power consumption values for the conventional jet fan and the MoJet are within the measurement uncertainties specified in Ref. [6] (±5% for thrust and ±2% for power consumption).

6. TUNNEL TEST RESULTS

The evaluation of the measured data results in the velocity profiles shown in figure 5. In both cases, the flow profile 140m downstream of the jet fan discharge is well developed and is reasonably evenly distributed over the tunnel cross–section. Certain areas with significantly higher velocities due to the discharged jet are not visible in either case, due to the long distance from the fan discharge. In the left part of the tunnel cross–section viewed in the direction of flow (right in figure 5), the MoJet reaches higher velocities overall. This is due to the swirl exhibited by the jet flow. Viewed in the direction of flow, the fan rotor turned in a counterclockwise direction. Since the discharged flow from the MoJet is deflected away from the soffit and towards the tunnel centre, this results in lower frictional losses. This allows the swirl to be maintained longer and to convey a larger volumetric flowrate in the left half of the tunnel cross–section.

With the MoJet silencers, an average air velocity in the tunnel of 3.78 m/s was achieved compared to an average air velocity of 3.33 m/s with conventional silencers, i.e. a 13.5% velocity increase with the MoJet. Since the thrust ratio is proportional to the square of the velocity ratio, it follows that the MoJet delivered 28.9% more in-tunnel thrust than the conventional jet fan. Since velocity measurements are subject to random errors estimated at ±3.5%, to 95% confidence (please refer to section 5 above), the measurements of the in-tunnel thrust will be subject to random errors estimated at ±7%.

The electrically absorbed power for the MoJet during the test was measured at 87.5 kW, which is 1.7 % higher than with conventional silencers (86.0 kW). These two power consumption measurements are however within the uncertainty limits in Ref. 6 (±2%).

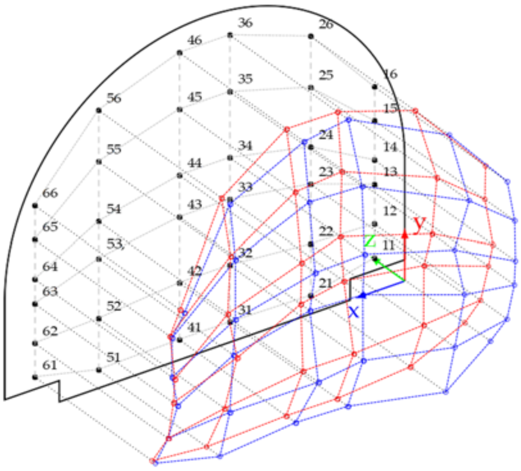

Figure 5: Measured velocity distribution for the conventional jet fan (in red) and the MoJet (in blue)

7. 3D CFD CALCULATIONS

The factory tests and tunnel measurements were modelled through 3D CFD, in order to better understand the flow physics and to gain confidence in future CFD modelling of similar cases.

Steady-state CFD models were built using ANSYS Fluent version 2022R1 and the effects of turbulence were resolved using the two-equation k-ω shear stress transport model. A single blade set at a pitch angle of 39.5° and rotating at 1485 rpm was modelled, with periodic boundary conditions used to simulate the remaining blades. Mixing planes were applied upstream and downstream of the rotor. The turbulence in the blade's boundary layer region were accurately captured by refining the computational grid with prism layers giving a maximum y^+ value of 25. In addition, prism layers were generated for all other wall boundaries. The maximum y^+ recorded for the bellmouth, the silencer and the internal components of the conventional jet fan and the MoJet was approximately 60. The jet regions were refined using conical refinement zones. The computational grid comprised approximately 6 million polyhedral cells for the bench thrust models and 9 million polyhedral cells for the tunnel models.

In order to compute the tunnel cases efficiently, only the first 225 m length of the branch tunnel was modelled, and the main tunnel was not included in the simulations. Instead, a loss coefficient was applied at the junction between the main tunnel and the Rendel Street branch tunnel, to simulate the aerodynamic losses through the main tunnel portals, along the main tunnel and at the entry to the branch tunnel. This entry loss coefficient ($\frac{1}{2}K\rho V^2$) was calibrated at K=2.895 in order to meet the measured tunnel velocity for the MoJet case. The same loss coefficient was used for the conventional jet fan calculations. In order to reflect the relatively rough tunnel surfaces, a sandgrain roughness was set to 70 mm for the roadway, and 80 mm for the soffit and walls.

Table 2: Bench thrust test CFD vs measurements

Fan Type	Fan Mass Flow (CFD)	Fan Air Density (CFD)	Fan Discharge Velocity (CFD)	Thrust (CFD)	Measured Thrust	% Difference (CFD to measurements)
	kg/s	kg/m^3	m/s	N	N	
MoJet	56.66	1.20	38.48	2179	2123	2.6%
Conventional	57.71	1.20	39.19	2260	2221	1.8%

Table 3: Tunnel test CFD vs measurements

Fan Type	Fan Mass Flow (CFD)	Fan Air Density (CFD)	Fan Discharge Velocity (CFD)	Average tunnel air velocity (CFD)	Average tunnel air velocity (measurements)	% Difference (CFD to measurements)
	kg/s	kg/m^3	m/s	m/s	m/s	
MoJet	63.63	1.20	43.27	3.78	3.78	(calibrated via tunnel entry loss coefficient)
Conventional	59.42	1.20	40.39	3.37	3.33	1.2%

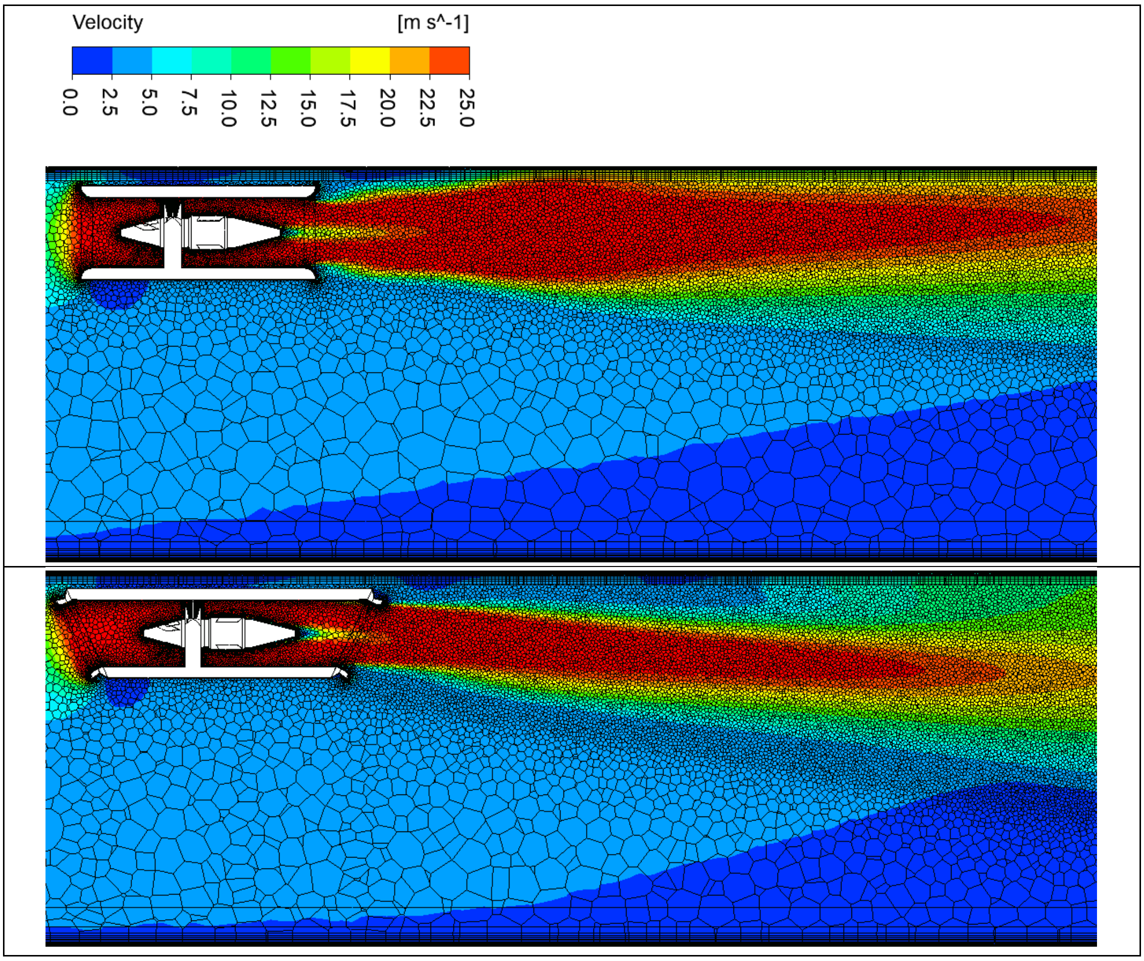

Figure 6: CFD-calculated velocity contours for a conventional jet fan (above) and for a MoJet (below)

The CFD-calculated velocity contours for the conventional jet fan (figure 6) show that the discharged jet attaches to the tunnel soffit, causing significant aerodynamic shear and loss of thrust. In contrast, the velocity contours for the MoJet show that the jet is deflected downwards by approximately 5°, such that the aerodynamic shear stress on the tunnel soffit is significantly reduced, and the in-tunnel thrust is increased. Another reason for the additional thrust of the MoJet in the tunnel is its 7% increased mass flow, compared to the conventional jet fan (table 3). This is due to the higher tunnel airflow in the MoJet case.

The installation factors implied by the CFD calculations were estimated using the following formula:

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

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 fan present in the tunnel domain [N]

V_T = Area-averaged longitudinal velocity in tunnel [m/s]

V_j = Jet longitudinal discharge velocity for bench thrust conditions, referred to the fan cross-sectional area [m/s]

The installation factors for the MoJet and the conventional jet fan were calculated on the basis of equation (2) and are presented in figure 7 below. The installation factor estimated using the Kempf correlation (Ref. [7]) is also presented in the same figure. The Kempf correlation generally over-predicts the installation factor for the conventional jet fan, and under-predicts the MoJet installation factor.

The installation factors for both the conventional jet fan and (to a lesser extent) the MoJet are predicted to decrease with increasing tunnel velocity, due to the stretching of the "friction patch" between the jet and the soffit. This phenomenon has been reported by other researchers, e.g. Ref. [8].

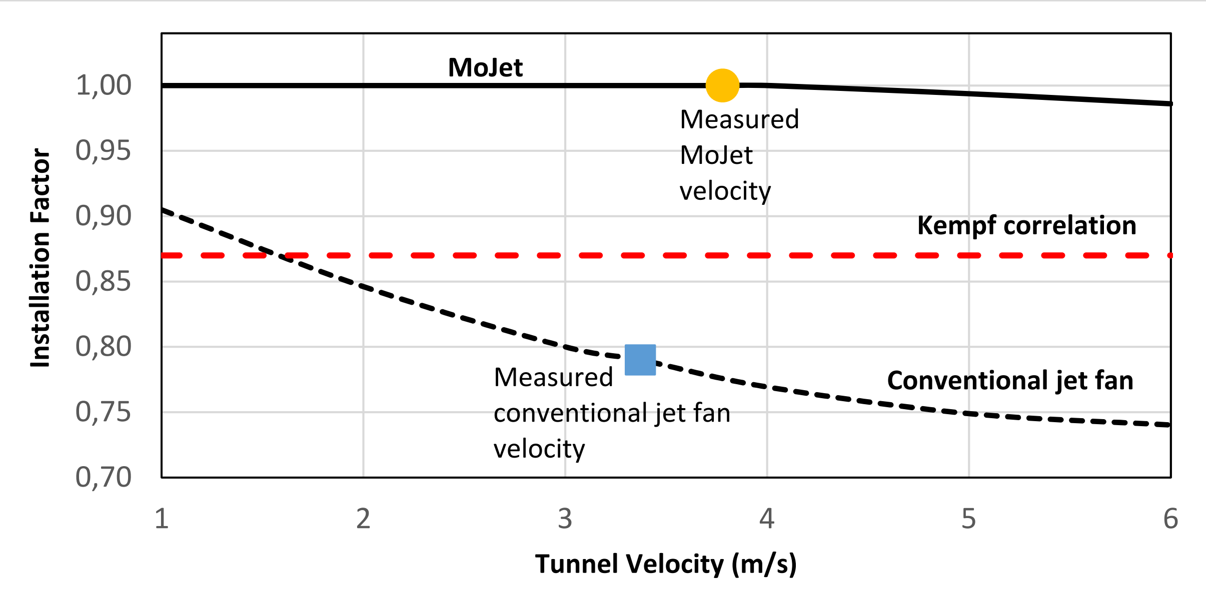

Figure 7: Jet fan installation factors estimated via 3D CFD

8. SUMMARY AND CONCLUSION

Our factory measurements of the bench thrust and power consumption of a conventional jet fan and a MoJet indicated approximately the same values, within the uncertainty limits defined in Ref. [6]. However, the two products behaved very differently within a tunnel, with the MoJet delivering almost 30% more in-tunnel thrust than a conventional jet fan. Our CFD calculations show that the main reason for this improvement is the significant reduction in the shear stress on the tunnel soffit with the MoJet, compared to a conventional jet fan. Another reason for the improved in-tunnel thrust with the MoJet is a 7% calculated increase in the mass flow through the fan, compared to a conventional jet fan. This is due to the shape of the inlet bellmouth, which has a larger cross-sectional area than the fan cross-sectional area.

Our findings suggest that the MoJet can be used to significantly reduce the required number of jet fans, and to substantially reduce the overall power consumption required for longitudinal tunnel ventilation. The actual reduction that can be achieved will be dependent on the specific tunnel geometry (including the surface roughness, which was high in the present case), as well as the ventilation design scenario – e.g. the fire heat release rate that is assumed, the number of jet fans assessed to be destroyed in a fire and the number of jet fans deemed to be out of service due to maintenance.

The research presented here considered only one jet fan installed within a tunnel at any given time. However, the majority of longitudinally ventilated tunnels require multiple jet fans to deliver the required airflow. In cases where the jets from upstream jet fans are ingested into downstream jet fans, a reduction in the jet fan thrust can be expected, due to the unloading of the fan blades (Ref. [2]). Such unloading can be expected to occur if the jet sticks to the tunnel soffit (or corner), and persists for a distance longer than the longitudinal spacing between the jet fans. It is likely that the deflection of the discharged jet away from the tunnel surfaces achieved by the MoJet will prove beneficial in avoiding the penalty of blade unloading, as well as reducing the aerodynamic shear downstream of the jet fans.

9. REFERENCES

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