TECHNOLOGIES FOR THE IMPROVEMENT OF JETFAN INSTALLATION FACTORS

Fathi Tarada, Karl Else
Mosen Ltd, UK

ABSTRACT

Three different technologies for the improvement of jetfan installation factors, namely deflection vanes, slanted silencers and MoJets, were calculated using 3D CFD and their performance was compared to that of a conventional jetfan. For a fixed installation height of 1.7 m, the MoJet exhibited an in-tunnel thrust enhancement of 61% above that of a conventional jetfan, with slightly reduced power consumption. Slanted silencers increased the installation factor compared to a conventional jetfan, but the in-tunnel thrust was reduced due to restrictions on the fan diameter. The deflection vanes tested in this study were not effective in increasing the in-tunnel thrust, due to the attachment of the jet to the tunnel floor.

Keywords: tunnel, ventilation, jetfan, installation factor, efficiency, thrust

1. INTRODUCTION

Alternative technologies have been proposed for the improvement of jetfan installation factors, including deflection vanes (with or without a clearance between the jetfan outlet and the vanes, Lotsberg (1997)), the Banana Jet (slanted silencers, Witt and Schütze (2008)) and the MoJet (a development on the original concept using silencers with an inclined outlet, Tarada (2018)). Each of these technologies implies different space requirements, power consumption, installation factors and induced tunnel velocities.

Bench thrust tests were simulated for a conventional jetfan and a MoJet to establish baseline values for the fan mass flow, power absorbed and axial thrust. The technologies were then tested in a tunnel environment and the values for the shaft power, axial thrust, tunnel airflow velocity and installation factor were calculated. The limitations of using the concept of installation factor in a strongly swirling, 3D flow-field in a tunnel are discussed.

2. CFD MODELLING

The calculations reported in this paper were undertaken using ANSYS CFX, a commercially available general-purpose CFD code.

A typical CFD model investigated in this study can be seen in **Figure 1** below. The model represents a 211.6 m long section of tunnel, within which a single jetfan is located along the tunnel centreline at the tunnel soffit, 52.8 m from the upstream end. The height of the tunnel is 6.75 m, and is 16 m wide.

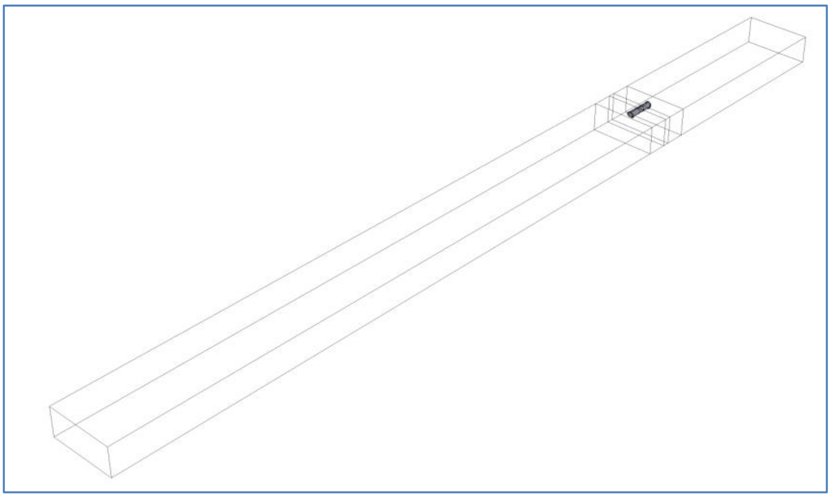

Figure 1: CFD Model of Tunnel including Jetfan

The detailed geometry of the jetfan hub, blades and motor was included in the same CFD model as the tunnel geometry. Blade rotation was simulated using the multiple frame of rotation option in ANSYS CFX, with circumferential averaging. The mass flow through the jetfans was not prescribed but was calculated through the CFD code based on a blade rotational speed of 1500 rpm, corresponding to the speed of a four-pole motor. Reductions in blade rotational speed due to induction motor slippage were not accounted for. The k-ω SST model of turbulence (Menter, 1993) was employed, which assisted in identifying any areas of flow separation. The tunnel walls, floor and soffit were assumed to have a uniform sand roughness height of 0.03 m, giving an equivalent friction factor (λ=4f) of 0.024.

Boundary layer meshes were attached to all solid surfaces to resolve sharp velocity gradients. Within the fans and silencers, these boundary layer meshes were calculated via 30-layer prisms with an initial layer approximately 0.1 mm thick within a jetfan, and with an expansion factor of 1.2 (**Figure 2**). Along the tunnel, the boundary layer mesh was 10-layer with an initial layer 0.3 m thick and an expansion factor of 1.1. A typical y^+ value for the last cell (downstream) along the (rough) tunnel surfaces was 315, while a typical y^+ value on the fan blades and silencers was 15. **Table 1** lists the number of CFD cells used for each type of technology tested.

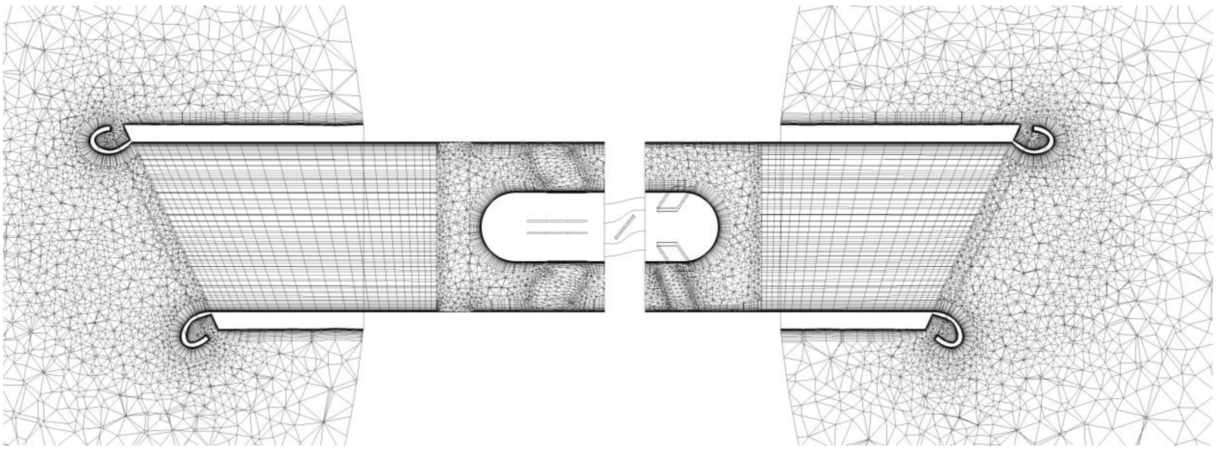

Figure 2: Mesh for MoJet Bench Thrust Test

Table 1: Number of CFD cells employed in the simulations

Technology	**Conventional jetfan**	**Deflection vanes**	**Slanted silencers**	**MoJet**
Number of CFD cells	25.1 million	72.3 million	25.6 million	27.1 million

3. TECHNOLOGIES INVESTIGATED IN THE STUDY

The four technologies selected for this study are well established in engineering practice (conventional jetfan, deflector vanes and slanted silencers) or represent a recent innovation (MoJet). The fan, casing, silencer and centrebody geometries for all four technologies were provided by a major manufacturer of tunnel ventilation equipment.

The same available installation height of 1.7 m was assumed for all four jetfan technologies. The silencers attached to the fans were selected with 100 mm thickness, and were arranged to be 150 mm below the tunnel soffit.

The jetfan internal diameter for the conventional jetfan, deflection vanes and MoJet was set at 1.25 m. A smaller jetfan diameter (1 m) had to be selected for the slanted silencers (with a 7° angle to the horizontal) to keep the jetfan to just within the 1.7 m installation height limit. All four technologies had “2D” lengths of silencers installed on either side of the fan, where “D” is the internal diameter of the fan.

A mid-range blade pitch angle of 33.4° was selected for the initial calculations with the 1.25 m diameter jetfans. A blade pitch angle of 39° was also tested for the MoJet, to approximately match the shaft power absorbed by the conventional jetfan.

The deflector vanes included a flat section followed by vanes set at 25° from the horizontal. Following the fan manufacturer’s guidance, the deflector vanes were installed at a distance of 0.504 m from the silencers at both ends of the jetfan (**Figure 3**).

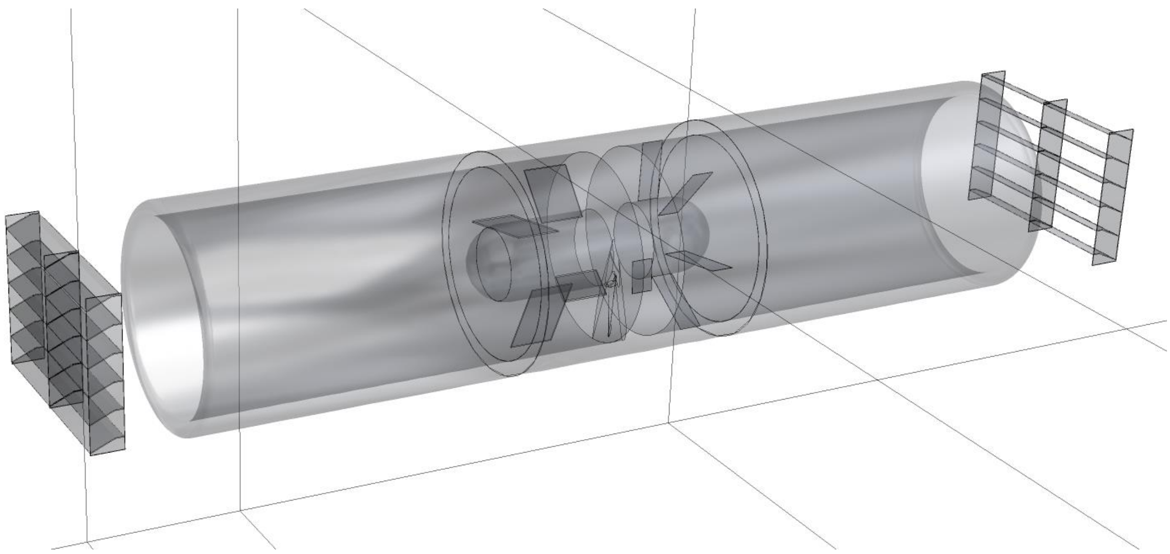

Figure 3: Jetfan with Deflector Vanes

4. CFD RESULTS

4.1. Bench Thrust Results

Bench thrust calculations were undertaken for the conventional jetfan and MoJet options, to provide a baseline for comparison with experimental data. The results are summarised in

Table 2. The density of air in still conditions can be taken as 1.185 kg m^{-3}. The fan shaft power was estimated as the product of the blade torque and the rotational speed in radians per second.

Table 2: Bench thrust results (1.25 m diameter fans)

	Conventional jetfan	**MoJet**
Blade pitch angle	33.4	33.4
Blade torque (Nm)	285.6	275.3
Fan shaft power (kW)	44.9	43.2
Fan mass flow (kg/s)	50.57	51.38
Thrust (N)	1759	1815

Compared to measurements, the calculated conventional jetfan thrust is overstated by around 5% due to the neglect of the induction motor slippage. The deviation of the MoJet thrust is expected to be less than 5%, because the reduced motor torque causes less slippage.

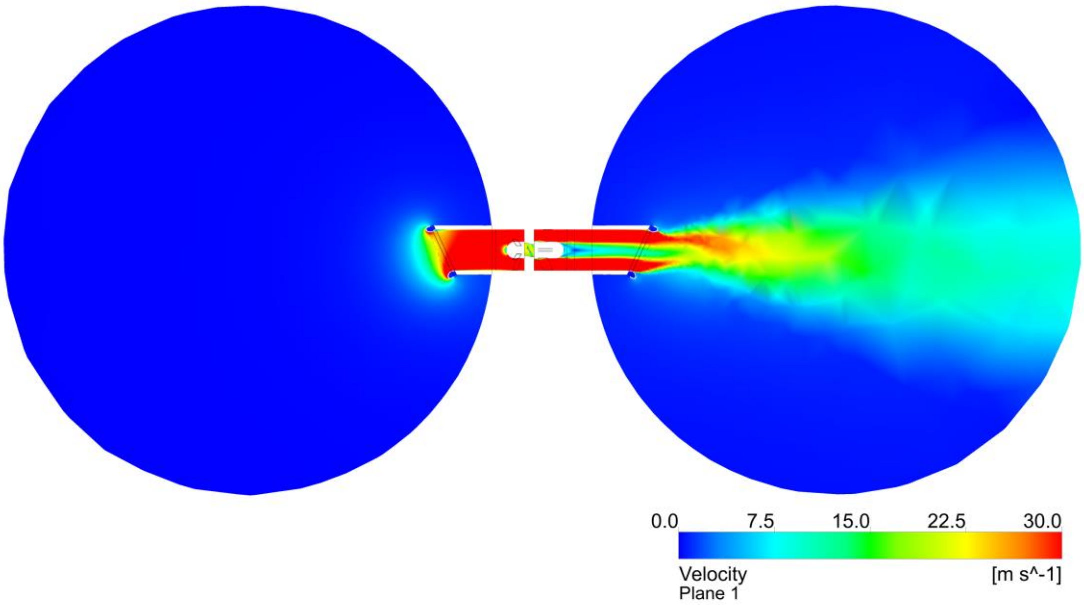

Figure 4: Bench Thrust Test for MoJet (Velocity Contours)

4.2. Tunnel Installation Results

The effective thrust of a jetfan in a tunnel, T, is lower than the bench thrust, due to confining effect of the tunnel soffit (which reduces the mass flow through the fan) and because of the friction on the tunnel walls, which is represented by the installation efficiency η_i. The value of T is calculated as:

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

where A_A is the cross section of the jetfan outlet, v_A the jet average velocity and v_T the velocity in the tunnel beyond the direct influence of the jetfan intake and discharge. The installation factors were interpreted from the CFD results on the basis of the methodology described by Tarada (2016), as follows:

$$\eta_i = 1 - \Delta T / T_{max} \qquad \text{(Equation 2)}$$

where

ΔT	= increase in skin friction drag above standard case
	= skin friction drag predicted by CFD – standard skin friction drag

and

Skin friction drag in 3D CFD = Sum of predicted wall, soffit and roadway drag forces

Standard skin friction drag = $\frac{1}{2}\rho v_T^2 \lambda \frac{LA_T}{D_h}$

where

L = tunnel length (m)

A_T = cross-sectional area of tunnel (m^2)

D_h = hydraulic tunnel diameter (m)

Since the installation factor relies upon one-dimensional consideration of the tunnel airflow, it may be of limited value in a tunnel with strongly swirling flow, such as jetfans with internal struts removed, as discussed below.

Table 3 summarises the jetfan performance values obtained in the study.

Table 3: Summary of Jetfan Performance

	Conventional jetfan	**Conventional jetfan (struts removed)**	**MoJet**	**MoJet**	**MoJet (struts removed)**	**Slanted silencers**	**Jetfan with deflectors**
Blade pitch angle	33.4	33.4	33.4	39	39	43	33.4
Tunnel airflow velocity (ms^{-1})	2.66	2.60	3.04	3.62	3.89	2.56	2.26
Installation factor	0.84	0.74	0.92	1.00	0.97	0.98	0.60
Fan shaft power (kW)	56.7	53.1	48.2	56.3	53.7	28.0	56.4
Fan mass flow (kg/s)	49.0	50.0	52.2	57.4	57.6	33.6	49.4
% of conventional jetfan in-tunnel thrust	100%	91%	124%	161%	156%	86%	74%

4.3. Conventional Jetfan

The jet discharged from a conventional jetfan adheres to the tunnel soffit due to the Coanda effect, causing a loss of in-tunnel thrust due to friction between the jet and the soffit.

When installed with 150 mm clearance to the tunnel soffit, the mass flow through the conventional jetfan is reduced by 6.1% from its bench test value, due to the confining effect of the soffit on the inlet silencer. Taking the reduced mass flow into account, the installation factor calculated from the CFD results is very close to the value provided by the Kempf correlation (1965):

$$\eta_i = \left[0.0192 \left(\frac{z}{D_A} \right)^2 - 0.144 \frac{z}{D_A} + 1.27 \right]^{-1} \qquad \text{(Equation 3)}$$

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. This result is somewhat surprising, since Kempf did not include any swirl in his measurements. The CFD calculations indicated a significant swirl velocity of up to 10 m/s at the discharge from the silencer following the fan (**Figure 6**). Removing the struts holding the fan centrebody (which is aerodynamically equivalent to replacing the struts with drop-rods) increases the outlet swirl, but neither improves the installation factor nor the tunnel airflow velocity.

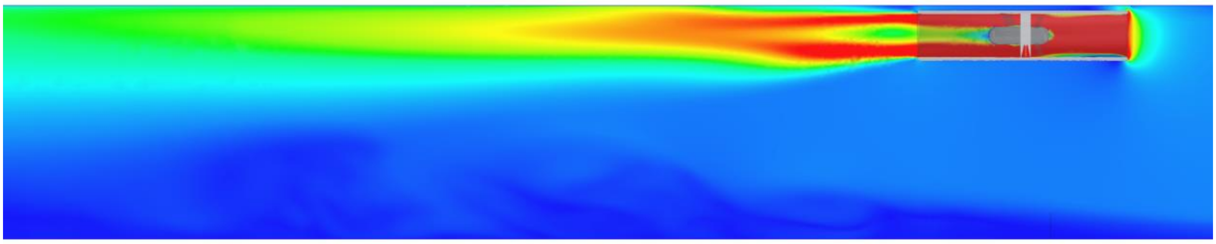

Figure 5: Velocity Contours for Conventional Jetfan (Colour Legend as per **Figure 4**)

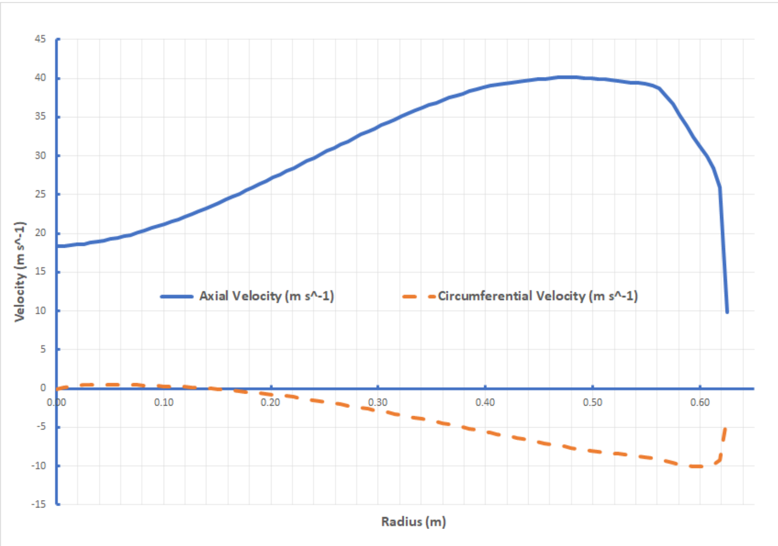

Figure 6: Axial and Circumferential Velocities at Discharge from Conventional Jetfan Silencer with Struts (33.4° Blade Pitch Angle)

4.4. MoJet

The MoJet design tested in these calculations comprises silencers with trailing edges that are inclined at 25° from the vertical. The trailing edge is circular in shape, with a diameter (1.379 m) greater than that of the fan (1.25 m). A convergent/divergent bellmouth is attached to the trailing edge, with a minimum diameter of 1.332 m. The bellmouth is designed to avoid separation of the flow at the lower edge of the MoJet inlet silencer, and the same bellmouth is designed to turn the flow at the upper edge of the MoJet discharge silencer.

Since the inlet and outlet areas of the MoJet silencer are significantly greater than the fan area, there is less resistance to the fan airflow, and the MoJet results therefore exhibit higher mass flow and less power consumption than conventional jetfans with the same blade pitch angle.

The increase in the cross-sectional area of the MoJet silencer leads to a significant pressure recovery downstream of the fan, and to a reduction in the discharge velocity. Approximately 22% of the kinetic energy of the flow is recovered as static pressure in the MoJet outlet silencer. This pressure recovery leads to an increase in the force exerted by the MoJet onto the tunnel air, while the reduction in discharge velocity reduces the aerodynamic friction between the jet and the soffit. The Coanda effect is also reduced by the effect of the bellmouth in turning the flow away from the tunnel soffit. These factors explain the high (near-unity) installation factors reported for the MoJet in **Table 3**.

The MoJet results for a 33.4° blade pitch angle show a 24% increase in the in-tunnel thrust compared to a conventional jetfan, with 15% less absorbed power. In order to compare the MoJet with a conventional jetfan of equivalent power consumption, the MoJet blade pitch angle was increased from 33.4° to 39°. This enhances the MoJet in-tunnel thrust to 161% of the conventional jetfan in-tunnel thrust, with slightly less power consumption than the conventional jetfan. Removing the struts (i.e. replacing them with drop-rods) reduces the installation factor slightly, but installation factor is an unreliable parameter for prediction of this complex swirling flow-field. Using drop-rods in a MoJet delivers a significant increase in the tunnel air velocity with less power consumption – arguably the main issues of interest to tunnel designers.

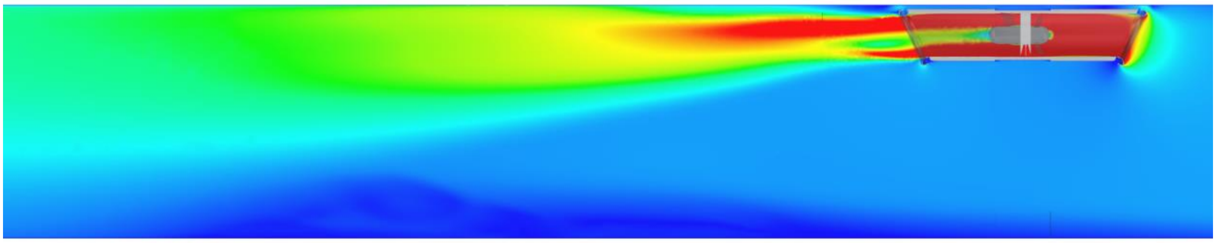

Figure 7: Velocity Contours for MoJet with 39° Blade Pitch Angle, with Struts (Colour Legend as per **Figure 4**)

4.5. Slanted Silencers

The installation factor is improved by the use of slanted silencers compared to a conventional jetfan, but this improvement does not adequately compensate for the loss of thrust due to the reduction of the jetfan diameter from 1.25 m to 1 m. This loss in thrust occurred even though the blade pitch angle was increased to the maximum allowable value without stalling, namely 43°. The in-tunnel thrust with slanted silencers is reduced to 86% of the conventional jetfan thrust, with a corresponding reduction in tunnel air velocity. The loss of thrust due to a reduction in fan diameter with slanted silencers would occur in any height-restricted space, and is not a result of the 1.7 m clearance assumed in this study. However, due to the reduction in fan diameter to 1 m, the thrust/power ratio with this option is better than any of the 1.25 m diameter fans tested here.

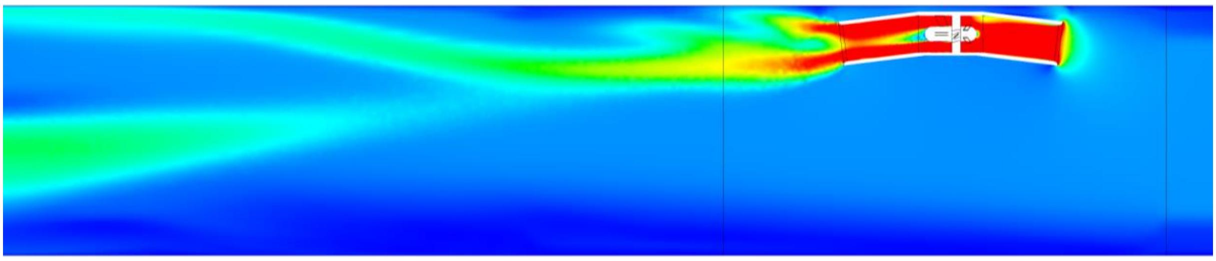

Figure 8: Velocity Contours with Slanted Silencers (Colour Legend as per **Figure 4**)

4.6. Jetfan with Deflectors

The result with deflectors shows that the swirl in the discharge flow is eliminated, and the flow is efficiently directed downwards (**Figure 9**). However, the jet then attaches to the tunnel floor, and significant friction is generated there. The installation factor is therefore rather poor at only 0.60, and the tunnel air velocity is less than that with a conventional jetfan. It is recognised that a better result could have been obtained by deflectors that are better designed. The authors contacted three fan manufacturers with a request for improved deflector geometry, but no response was received.

The authors originally planned to test the same deflectors coupled directly to the ends of a jetfan. However, given the poor performance observed with the detached deflectors, the CFD calculations with the coupled deflectors were abandoned.

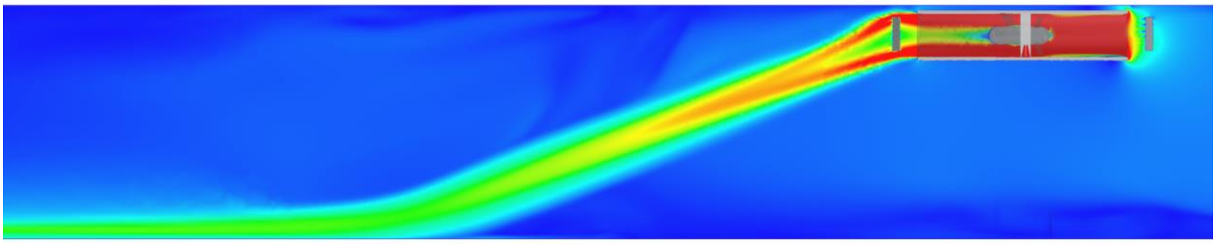

Figure 9: Velocity Contours with Deflectors (Colour Legend as per **Figure 4**)

5. CONCLUSIONS

Each technology that purports to improve the tunnel installation factor can have an effect on the jetfan itself (e.g. in terms of reduced or enhanced mass flow), as well as having an effect on the tunnel air (e.g. by deflecting the jet away from the tunnel soffit, or enhancing the pressure force exerted on the tunnel air). The most promising technology identified by this study has been the MoJet, which can increase the in-tunnel thrust by 61% above the conventional jetfan value, with a slightly reduced power consumption. A research project is underway at the Institute of Aerodynamics at RWTH Aachen University to manufacture 1:18 scale models of jetfans with different silencer geometries including slanted silencers and MoJets using 3D printing, and to measure their tunnel installation factors. Full-scale tests of MoJets in a tunnel are also planned.

6. REFERENCES

Kempf, J. (1965), *Einfluss der Wandeffekte auf die Treibstrahlwirkung eines Strahlgebläse*s, Schweizerische Bauzeitung, 83. Jahrgang, Heft 4, Seiten 47-52.

Lotsberg, G. (1997), *Investigation of the Wall-friction, Pressure Distribution and the Effectiveness of Big Jetfans with Deflection Blades in the Fodnes Tunnel in Norway*, 9th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Aosta Valley, Italy.

Menter, F. R. (1993), *Zonal Two Equation k-ω Turbulence Models for Aerodynamic Flows*, AIAA Paper 93-2906.

Tarada, F. (2016), *Innovation in Jetfan Design*, 7th International Symposium on Tunnel Safety and Security, Montreal.

Tarada, F. (2018), *Optimised Tunnel Ventilation Device*, International PCT Patent Application Number PCT/GB2018/000029.

Witt, K.C. and Schütze, J. (2008), *Effective Thrust Transformation inside Tunnels with Jet Fans (Banana Jet)*, 4th International Conference 'Tunnel Safety and Ventilation', Graz.