Impulse ventilation for tunnels – a state of the art review

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Impulse ventilation is a powerful means by which airflow can be enhanced in tunnels, by the application of one or more jets of air in the desired direction. The choice of impulse ventilation solutions, until recently limited to Saccardo nozzles and jetfans, have been enhanced by recent inventions including the Banana Jet®, MoJet© and fresh-air impulse dampers. This paper provides a state of the art review of these alternatives, including their theory and applications, and provides guidance on their advantages and drawbacks.

1 INTRODUCTION

Impulse ventilation of tunnels involves the application of one or more jets of air into a tunnel, to drive the airflow in a desired direction. In essence, the kinetic energy of a high-velocity jet is transferred, with various degrees of efficiency, into the kinetic energy of slower-moving tunnel air. Inefficiencies occur in the transfer of energy because a fraction of the air jet's momentum is lost due to frictional drag on tunnel surfaces, and due to form drag on any bluff bodies that the jet impinges upon.

A number of devices are available to provide impulse ventilation in tunnels, including Saccardo nozzles and jetfans, along with more recent inventions, including the Banana Jet®, MoJet© and the fresh-air impulse dampers. Each of these devices presents the designer with issues with regards to their suitability to deliver the required aerodynamic thrust; their capital and maintenance costs; and the ventilation system power requirements. The purpose of this paper is to present a brief overview of impulse ventilation for tunnels, to outline the impulse ventilation devices currently available, and to give guidance regarding their advantages and drawbacks.

Systems used in order to reduce the longitudinal flow such as physical blockages and air curtains are beyond the scope of this paper.

2 SACCARDO NOZZLES

2.1 Introduction

Saccardo nozzles (otherwise called "Saccardo ejectors" or "impulse nozzles") introduce an air jet into a tunnel, at a high velocity of around 30m/s. This air jet imparts most of its momentum to the tunnel air, and hence helps to drive the tunnel air in the desired direction. Marco Saccardo patented an 'Improved Method and Apparatus for Ventilating

Tunnels' in UK patent number 2026, dated 1898. This original patent described the use of air jets to ventilate railway tunnels.

Saccardo nozzles supply external air into a tunnel by fans situated in a fan chamber outside the tunnel (Figure 1). This fan chamber is conventionally constructed above a tunnel portal or shaft, where the air is drawn from outside, and then supplied into the tunnel at a shallow angle to the tunnel longitudinal axis (typically, at an angle of 30 degrees or less). A shallow angle is normally selected, in order to align the jet with the tunnel axis and hence maximise the potential thrust that can be generated, and to avoid high-velocity jets inconveniencing or endangering tunnel users. In addition, caution should be taken in order to prevent the jet from attaching to the tunnel surfaces, in order to minimise the frictional losses encountered by the jet. The jet is generally attracted to the tunnel surfaces due to the 'Coanda effect' – a reduction in static pressure due to the high jet velocity, which tends to deflect the jet towards a solid surface.

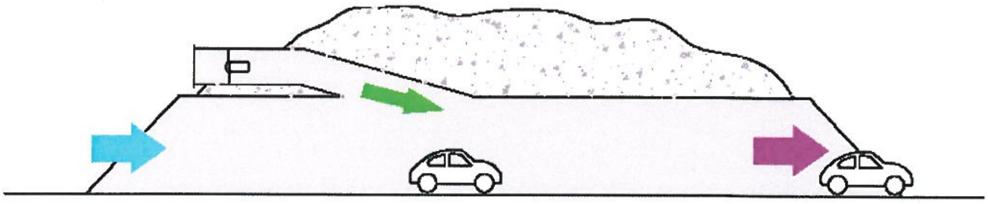

Figure 1: Longitudinal ventilation with a Saccardo nozzle (from PIARC 2008)

The key advantages of Saccardo nozzles compared to jetfans have been summarised by Bendelius (1999) as follows:

1. Reduced tunnel height
2. Reduced number of moving parts to maintain
3. Maintenance can be accomplished without impeding traffic flow
4. Noise level in tunnel is decreased
5. High fan efficiency

The thrust imparted by air jets flowing from a Saccardo nozzle to the tunnel air can be described through the following momentum exchange equation:

$$T = \dot{m} V_j \eta_j \cos(\theta) \qquad \text{(Equation 1)}$$

where

T = Thrust imparted from the air jet to the tunnel air [N]
$\dot{m}$ = Mass flow of air jet [kg/s]
V_j = Velocity of air jet [m/s]
η_j = Installation efficiency [-]
θ = Angle between the jet and the tunnel axis [radians]

In the above equation, the installation efficiency η_j can either reduce (η_j <1) or increase (η_j >1) the thrust, depending on a function of a number of aerodynamic parameters. Irreversible processes such as friction of the jet along the tunnel soffit or floor will cause a reduction in the installation efficiency, typically to a value below unity. However, it has been reported by Tabarra et al (2000) in that a non-uniform tunnel velocity profile can lead to a value of installation efficiency (called 'momentum exchange coefficient' in the above-said paper) above unity.

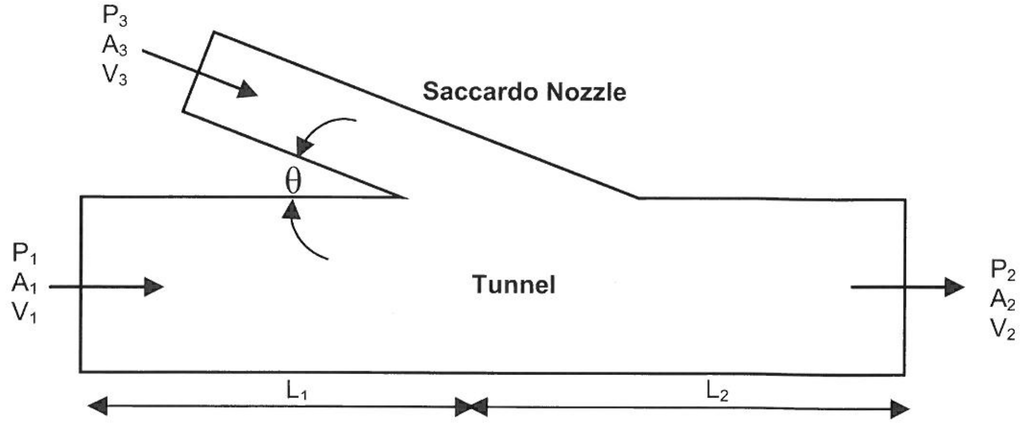

Figure 2: Momentum Control Volume for Saccardo Nozzle

The steady-state longitudinal momentum equation for a control volume in the immediate vicinity of a Saccardo nozzle (Figure 2) can be written as

$$(P_1 - P_2)A_2 = \dot{m}_2 V_2 - \dot{m}_1 V_1 - \dot{m}_3 V_3 \eta_j \cos(\theta) \qquad \text{(Equation 2)}$$

In the derivation of equation 2, it has been assumed that A_2=A_3, i.e. the tunnel cross-sectional area does not change across the Saccardo nozzle.

By considering mass continuity, it can be shown that equation 2 implies that the static pressure rise coefficient in the immediate vicinity of a Saccardo nozzle, ζ_{23}, can be given by

$$\zeta_{12} = \frac{P_1 - P_2}{\frac{1}{2}\rho V_2^2} = \varepsilon[2 - \varepsilon\{1 + \frac{\eta_j \cos(\theta)}{\alpha}\}] \qquad \text{(Equation 3)}$$

where

$$\varepsilon = \frac{V_3 A_3}{V_2 A_2} \quad \text{and} \quad \alpha = \frac{A_3}{A_2}$$

Equation 3 implies that the static pressure downstream of a nozzle will rise, as long as sufficient air flowrate is supplied through the nozzle to ensure that

$$\varepsilon > \frac{2}{(1 + \eta_j \cos(\theta) / \alpha)} \qquad \text{(Equation 4)}$$

There are two main operating modes for Saccardo nozzles: the (generally desirable) flow induction mode, where air is drawn from the portal into the tunnel, and the (generally undesirable) flow rejection mode, where air is discharged from the portal. By referring to the Bernoulli equation, Tabarra et al (2000) derived a number of equations describing the airflow for each mode, but these equations suffer from a number of drawbacks, including the neglect of the outlet loss coefficients. If the equations had been treated properly by

Tabarra et al, a single equation would apply to both the flow induction and the flow rejection modes:

$$\omega^2\left[\alpha^2\left\{1-\frac{1}{2}(K_1+f\frac{L_1}{D_h})\right\}+\alpha\eta_j\cos(\theta)\right]+\omega\alpha\left[K_1+f\frac{L_1}{D_h}-2\right]-\frac{1}{2}\left[K_1+f\frac{L_1}{D_h}+K_2+f\frac{L_2}{D_h}\right]=0$$

(Equation 5)

Equation 5 is a quadratic equation for the velocity ratio $\omega=V_3/V_2$, where K_1 and K_2 refer to the entry or exit loss coefficients at the left and right hand portals depicted in Figure 2 respectively, f is the tunnel friction factor ($f=\Delta P/\{½\rho V^2\}/\{L/D_h\}$), and D_h is the hydraulic tunnel diameter.

2.2 Practical applications

2.2.1 Conventional Saccardo nozzles

Hofer & Co (1899) and the article in Schweizerische Bauzeitung (1899) describe the Saccordo system used for the Gotthard rail tunnel. Another early application is in the 640 m long Rendsburg tunnel that was constructed in the 1950's.

One of the most recent applications is for the refurbishment of the 650 m long Holmesdale tunnel on the M25 (UK) that was reopened in 2007. An important factor when opting for the Saccardo system was the maintainability of the tunnel ventilation system without having to enter the traffic space, in order to ensure high availability of the tunnel.

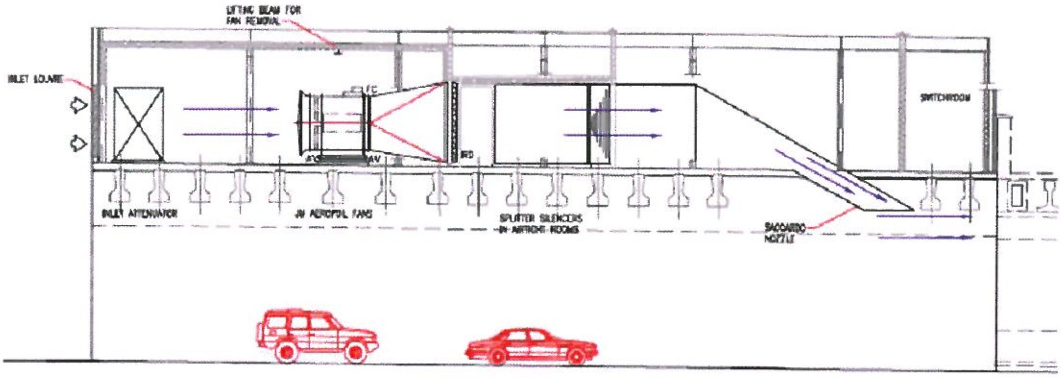

Figure 3: Holmesdale Tunnel Saccardo Nozzle Arrangement (Kenrick, 2008)

2.2.2 Fresh-air impulse dampers

The combination of fresh-air injection and ventilation control has been developed and patented, Pischinger (2002) and Almbauer et al (2003). Such a system has already been implemented and successively tested e.g. in the Katschberg tunnel, Sturm et al (2008). It consists of a damper used for fresh-air injection and a blocking element in the fresh-air duct sealing off the remaining of the fresh-air duct, see Figure 4. By increasing/reducing the air volume and in certain cases also the angle of the injection nozzle, it is possible to control the air velocity inside the tunnel.

Pruckmayer et al (2008) describe using a multi-leaf damper where the opening angle can be varied from 15° to 140° at the fresh-air injection point. In this manner, the flow can be directed in both axial directions into the tunnel tube.

In addition to altering the opening angle of the damper, the impulse can be varied by changing the flow rate of the supply fan.

Figure 4: Fresh-air impulse device: damper (left), blocking element closed (centre), blocking element open (right)

2.2.3 Bi-directional Saccardo nozzles with constant injection angle

Saccardo nozzles can be designed to work in both flow directions, with dampers or flaps to direct the airflow in one direction or another, see Figure 5.

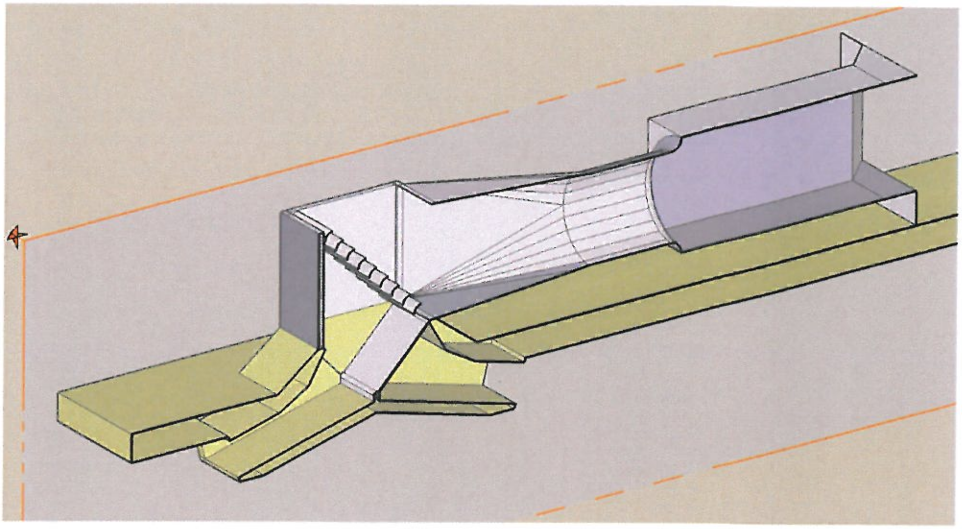

Figure 5: Saccardo nozzle that can operate in both flow directions (axial cut)

3 JETFANS

3.1 Introduction

Jetfans, also called booster fans, provide an impulse to the air flow, but do not add or remove air from a tunnel. The air is extracted on the suction side of the jetfan and expelled at high velocity on the outlet side. The average jet velocity is in the range of 30 to 40 m/s.

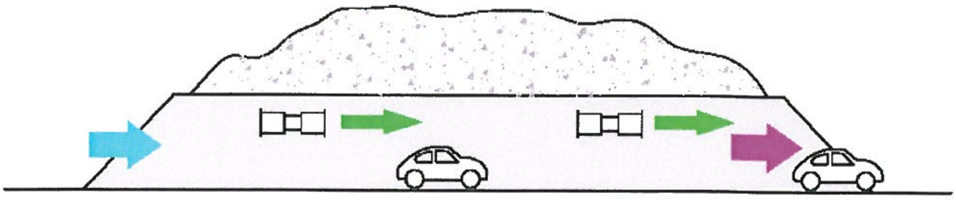

Figure 6: Longitudinal ventilation with jetfans (from PIARC 2008)

3.2 Conventional jetfans

Conventional jetfans blow the air straight in the axial direction of the impeller and are normally aligned parallel to the tunnel axis.

The principle was promoted in the 1960's and is described by Rohne (1964). Following Truckenbrodt (1980), the maximal achievable thrust is calculated as (see Figure 7):

$$T_{\max} = \frac{\rho}{2}\frac{A_1 A_2}{\left(A_1 - A_2\right)^2}\left[\left(2A_1 - 3A_2\right)v_2^2 - 2\left(A_1 - 2A_2\right)v_1 v_2 - A_2 v_1^2\right] \qquad \text{(Eqn. 6)}$$

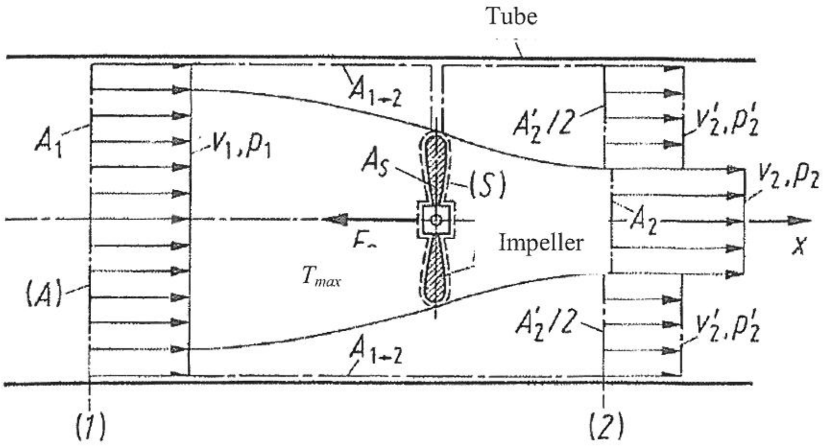

Figure 7: Jetfan in a tube, nomenclature according to Trockenbrodt (1980)

For example: at a density ρ of 1.2 kg/m^3, a tunnel air flow v_1 of 2 m/s and jet velocity v_2 of 30 m/s gives in a tunnel with a cross section A_1 of 60 m^2 and a jetfan outlet cross section A_2 of 1 m^2 a maximum thrust T_{max} of 1017 N.

However, for practical application, following simplified model of an impeller in a free stream is normally used:

$$T_{\max} = \rho A_A v_A (v_A - v_\infty) \qquad \text{(Equation 7)}$$

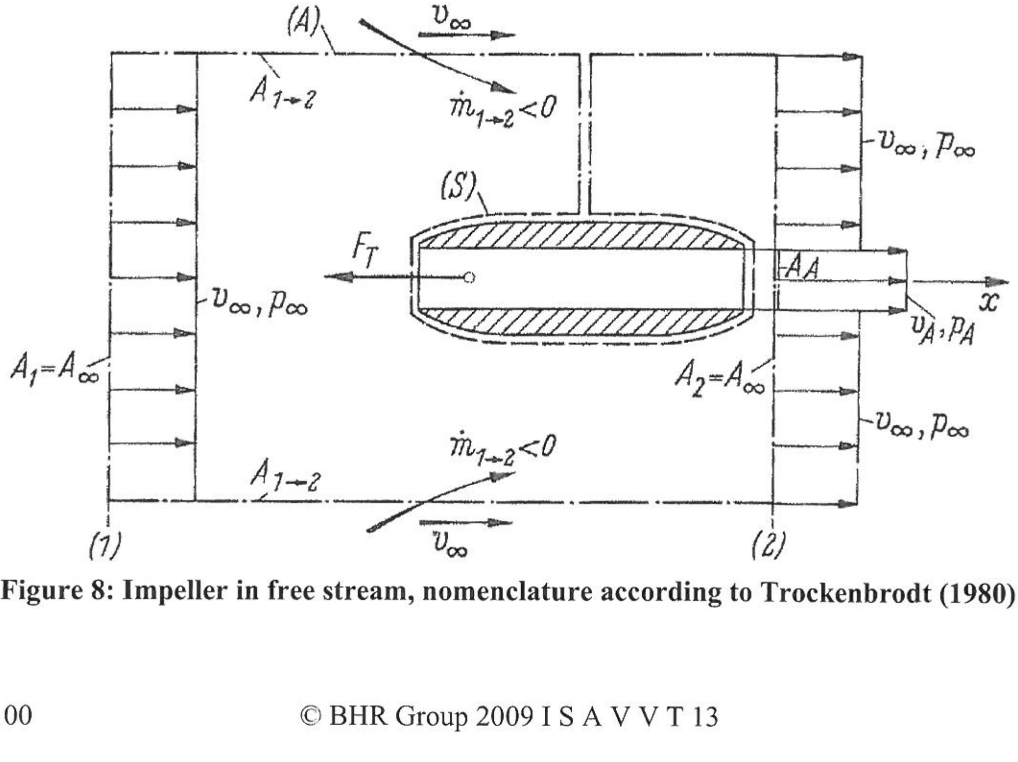

Figure 8: Impeller in free stream, nomenclature according to Trockenbrodt (1980)

The simplified Equation 7 gives values that are typically 2 to 3 % lower than those derived by the accurate Equation 6 according to Figure 7.

These theoretical computations of the maximum thrust inherently assume that the flow rate through the jetfan does not exceed the flow rate in the tunnel.

The effective thrust, T, is lower due to the jetfan efficiency, η_f, and installation efficiency η_i. The value of T is calculated as:

$$T = \eta_i \cdot \eta_f \cdot \rho A_A v_A (v_A - v_\infty) \qquad \text{(Equation 8)}$$

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

The jetfan efficiency η_f is conventionally employed to resolve differences between the catalogue values of thrust and jet velocity. Since BS 848-10:1999 (ISO 13350:1999) prescribes a significantly tighter measurement uncertainty (±5%) for jetfan thrust compared to the jet velocity (±10%), designers normally use the catalogue jetfan thrust values to 'back-calculate' the jet velocity. In this case, it can be assumed that η_f=1.

The installation efficiency η_i takes the value of unity (1) if the jet is situated in the middle of the tunnel and is not influenced by adjacent jetfans, obstacles and tunnel surfaces. Alternatively, if the jetfan is located adjacent to the tunnel wall, η_i=0.85 and for a jetfan in a corner of a rectangular cross-section tunnel, η_i=0.73. In case of locating jetfans in niches, the niche angle should not exceed 10° in order to keep the friction losses to a minimum.

An interpolation of the experimental data by Kempf (1965), gives following estimates of the installation efficiency

$$\eta_i = 0.0192\left(\frac{z - 0.5 \cdot D_A}{D_A}\right)^2 - 0.144\frac{z - 0.5D_A}{D_A} + 1.27\,, \qquad \text{(Equation 9)}$$

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.

The efficiency of the jetfans can be significantly reduced if they are located too closely apart in the longitudinal direction, since a certain spacing is required to allow the velocity profile in the tunnel to develop (see left hand side of Figure 9). The usual guidance states that a minimum longitudinal distance of ten times the tunnel hydraulic diameter should be maintained, although some references state that jetfans should be located at a certain minimum distance such as 80 m or 100 m apart, and other references specify a hundred times the jetfan diameter as the minimum longitudinal distance. In the direction of the discharge jet, the same distance has to be observed between a jetfan and a tunnel portal. Finally, care should be taken that the jet can freely develop and is not impaired by physical obstacles, e.g. variable message signs. However, no such requirement exists on the suction side of the jetfan.

3.3 Jetfans with angled outlet: guide vanes and slanted silencers (Banana Jet®)

As shown above, the installation losses due to placing the jetfans near the vicinity of the tunnel surfaces typically amounts to 15 % to 27 %. Kempf (1965) demonstrated the benefit of directing the flow away from the wall by using guide vanes or slanting the outlet. As guide vanes at the outlet of the jetfan increases the losses by few percent, they are primarily of benefit when the jetfans are located in close vicinity to the wall. Alternatively, the silencer can be slanted away from the wall.

Slanting the silencer away from the wall was used in the Feuerbachtunnel (Stuttgart, Germany) that was inaugurated in 1995. Model measurements of a slanted jetfan were conducted by Martegani et al (2000) and Jacques and Wauters (1999). Jacques and Wauters (1999) concluded that 7° to 8° would an optimal pitch angle. Analysing the experimental data, slanting the jetfan by this amount resulted in an increase in the installation efficiency by about 2.5 percentage points (e.g. increasing the value of η_i from 90.0 % to 92.5 %).

Assessing the possible benefits by slanting silencers using field measurements is challenging, as the anticipated improvement in performance is at the same order of magnitude as the measurement error, which is typically about 10 % for single flow measurements. Nevertheless, two measurements campaigns were conducted where so-called Banana Jets were installed. In both cases, the jetfans were adapted by inserting a triangular fitting between the silencer and the impeller unit in order to mimic the conventional, straight jetfan. This means, however, that the outlet of the conventional jetfan was closer to the wall than for the Banana Jet configuration, leading to higher installation losses for the straight jetfan.

For the two jetfan configurations, Figure 9 shows a comparison of the velocity profiles at various downstream positions. Firstly, it is noted that at distances between 60 m and 120 m downstream of the jetfan, the velocity profile becomes uniform i.e. there is no visible impact of the jet. Secondly, the velocity profile measured closer to the jetfan is more uniform for the Banana Jet than for the straight jetfan.

In the first measurement campaign (Pospisil et al., 2003), the measurements error in case of comparing two flow measurements was ±19 %. Considering the measurement accuracy, it was concluded that the thrust of the jetfans with slanted silencers was between 23% lower and 94 % higher than the one for the jetfans with conventional jetfans.

In the second measurement campaign (Marti and Brandt, 2004), improvements in the measurement technique reduced the measurement error in the comparison of two flow fields to ±12 %. Here, the jetfans were mounted in the corners of a rectangular tunnel section. The slanted silencers were directed towards the middle of the tunnel. It was concluded that the thrust of the Banana Jet was between 11 % and 21 % higher than the one of conventional straight jetfans.

It appears that by slanting the silencer about 7°, an installation efficiency of almost unity can be obtained. Compared to conventional straight jetfans, this corresponds to a higher thrust of typically between 15 % and 25 %.

In our experience, there is some risk with Banana Jets that the jet will attach itself to the tunnel floor, and move forward as a ‘wall jet’. The air velocity above the wall jet may be less than the critical velocity for smoke control, possibly leading to localised smoke back-layering. This issue may need to be addressed during the design stage of a project.

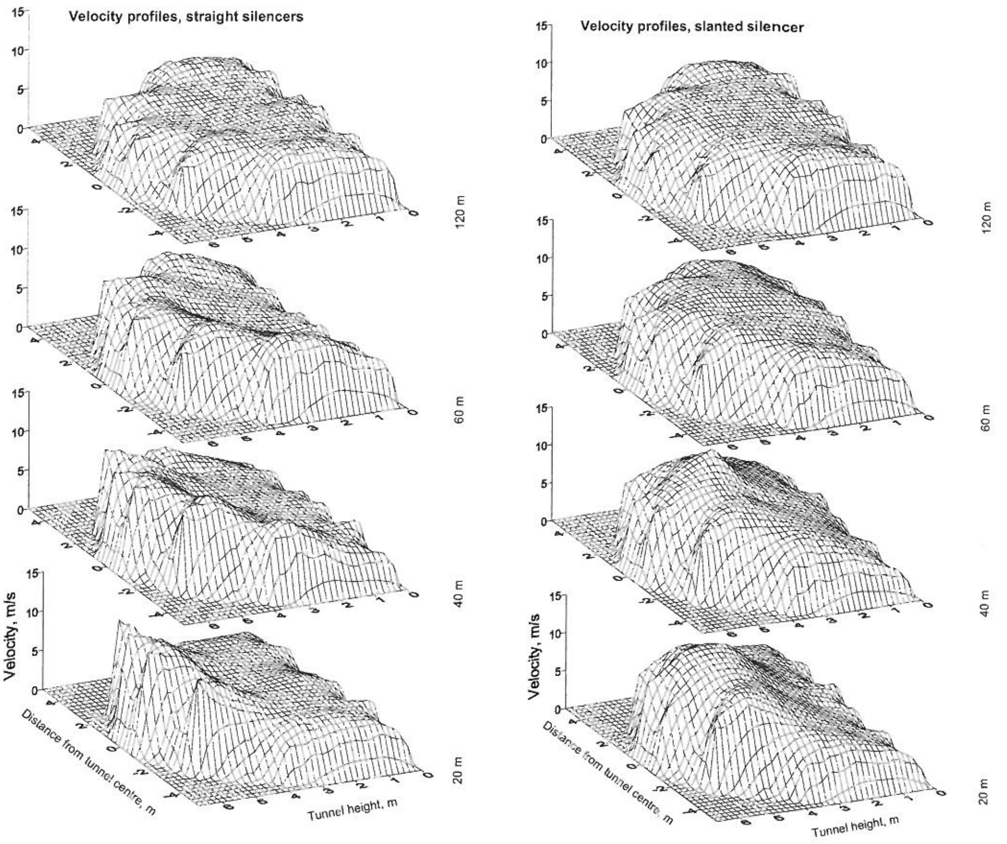

Figure 9: Velocity measurements in tunnel with conventional jetfans (left) and jetfans with slanted silencers (right), Pospisil et al 2003

3.4 Jetfans with Convergent Nozzles (MoJet©)

MoJet (*Mo*mentum *Jet*) is a recent innovation which combines a higher thrust akin to Saccardo nozzles, with high installation efficiencies similar to Banana Jets (Tarada, 2008). This is achieved by using convergent nozzles either on one or both sides of jetfans. The nozzles, which can also act as silencers, enhance the thrust of a conventional jetfan by accelerating the flow velocity at discharge from the jetfan. As long as the mass flow through the jetfan is not significantly reduced due to the additional pressure drop across the nozzle, an enhanced aerodynamic thrust will be achieved, as per Equation 7.

The same nozzles also direct the flow towards the centreline of a tunnel, hence can achieve installation efficiency (η_i) of near unity. Figure 10 shows unidirectional MoJets installed in the vicinity of a tunnel portal, with bidirectional MoJets installed within the tunnel.

The effect of mounting a convergent nozzle on a jetfan on the operating point of a fan is depicted in Figure 11. The figure indicates that when a nozzle is fitted to a fan, the volumetric flowrate drops from V_1 to V_2. However, V_2 is still greater than V'_1, where V'_1 lies on a constant power line from V_1. Hence, as long as the new operating point is below the fan's stall line, it is likely that the installation of a convergent nozzle would lead to an increased thrust produced by the fan. The reason for this is that a fan pressure versus volumetric flowrate characteristic for a given speed and blade configuration is generally steeper than a constant-power relationship between pressure and volumetric flowrate, when the modified operating point is compared to the original operating point.

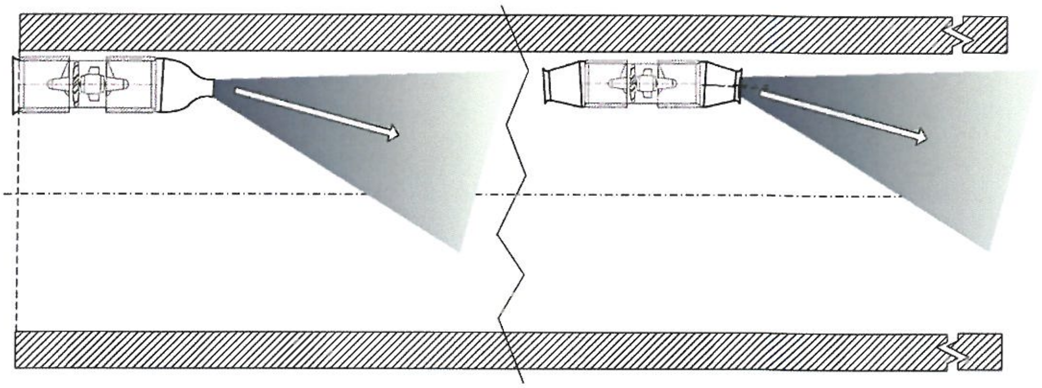

Figure 10: Undirectional and Bidirectional MoJets Installed within a Tunnel

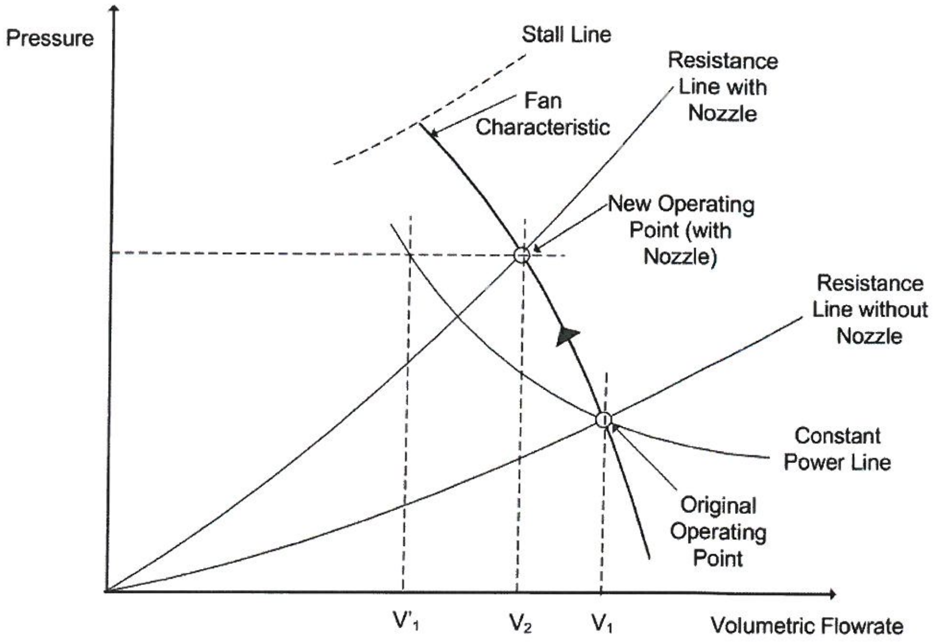

Figure 11: Fan Operating Characteristic with MoJet

Compared to the thrust generated by a jetfan without nozzles, an enhancement in the thrust of a ventilation device with a nozzle is achieved when the fan characteristic is 'steep' enough to satisfy

$$-\frac{\partial P}{\partial \dot{V}} > \frac{2\rho v_A^2}{\dot{V}}$$ for a unidirectional MoJet (Equation 10)

and

$$-\frac{\partial P}{\partial \dot{V}} > \frac{2(1+K_{in})\rho v_A^2}{\dot{V}}$$ for a bidirectional MoJet (Equation 11)

where

$\dot{V}$ = Volumetric flow of air through the ventilation device [m^3/s]
K_{in} = Inlet loss coefficient to nozzle (≈0.5 to 0.6)

A number of simplifying assumptions have been made in the derivation of equations 10 and 11 above, including:

- The pressure drop through the nozzles is assumed to dominate the overall fan pressure drop;
- The jet velocity V_j is assumed to be much greater than the tunnel air velocity V_T ;
- The fan characteristic ($P-\dot{V}$ curve) is assumed to be linear within the relevant range.
- The wall friction within the nozzles is assumed to be small.

Figure 12 shows the influence of the nozzle area ratio on the thrust of a 1.12m diameter jetfan, while Figure 13 shows the variation of absorbed power for the same jetfan. The following data was used in this exercise:

1. The unidirectional jetfan selected was a Fläkt Woods 112JM/40/4/9/24 with a guide vane.
2. The bidirectional jetfan selected was a Fläkt Woods 112JM/40/4/9/26 TS without a guide vane.

The figures in these examples show that an enhancement in longitudinal thrust of up to 20% can be achieved for the unidirectional case, and up to 12% in the bidirectional case. The power requirement increases approximately linearly with increasing nozzle area ratio, e.g. an increase of 27% in absorbed power would be required to achieve the peak bidirectional thrust.

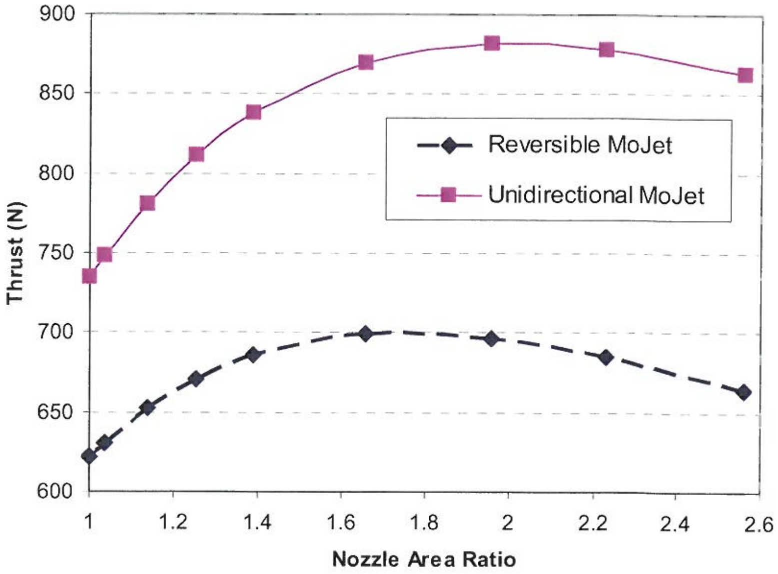

Figure 12: Influence of Nozzle Area Ratio on 1.12m Diameter Jetfan Thrust (after Crouzier, 2008)

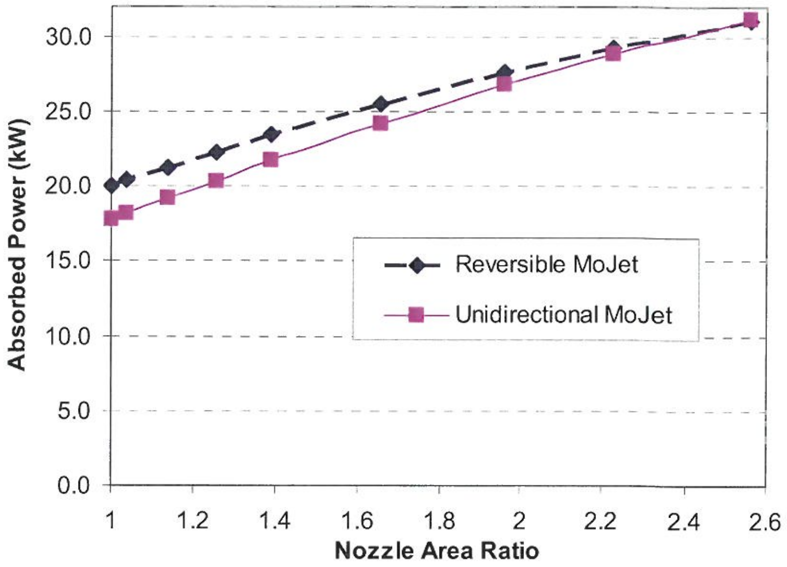

Figure 13: Influence of Nozzle Area Ratio on 1.12m Diameter Jetfan Power (after Crouzier, 2008)

4 CONCLUSIONS

Designers opting for impulse-ventilation techniques have a broader range of tools available at their disposal today, and can therefore select products that are suitable for their requirements.

Saccardo systems are usually installed close to the portals. The thrust they can achieve per unit power is, generally speaking, lower than that for conventional jetfans. However, they are easier to maintain as the sensitive parts of the installations are accessible from outside of the traffic space. This helps assuring a higher availability of the ventilation system and consequently possibly of the tunnel. Moreover, no additional traffic space in order to encompass jetfans is required, which again may lead to lower costs of the civil structures.

In case of tunnels with a semi-transverse fresh-air ventilation system, fresh-air impulse dampers can be installed at low additional costs.

By slanting the silencers of jet away from the tunnel wall, installation efficiencies close to unity appear to be achievable. Otherwise, for jetfans situated close to the tunnel wall but not in a niche, minimum installation efficiencies between 73 % (jetfan in corner of rectangular tunnel) and 85 % (jetfan at tunnel wall) are normally to be expected. On the other hand, slanting the silencer increases the overall dimension of the jetfan unit which can have implications on tunnel space requirements. For jetfans situated at the tunnel wall with no space to slant the silencer, use of turning vanes at the outlet of the jetfans increases the overall efficiency.

The shaping of jetfan silencers as convergent nozzles to enhance the thrust and improve the installation efficiency has been proposed. This appears to enable a significant reduction in the required number of jetfans in a tunnel, but could require larger power requirements per jetfan.

5 REFERENCES

Almbauer, R.A., Sturm, P.J., Öttl, D., Bacher, M. (2003), A new method to influence the air flow in transverse ventilated road tunnels in case of fire. In: Proceedings of the Conference Ventilation of Tunnels, BHR Group 2003.

Bendelius, A.G. (1999), 'Tunnel Ventilation' in 'Tunnel Engineering Handbook', ed. Bickel, J.O., Kuesel, T.R and King, E.H., 2nd edition, Chapman & Hall.

British Standards Institute (1999), 'Fans for general purposes – Part 10: Performance testing of jet fans', BS 848-10:1999 (ISO 13350:1999).

Crouzier, Y. (2008), 'Excel calculations with jetfans and nozzles', unpublished.

Hofer & Co. (1899), "Ventilationsanlage für den Gotthardtunnel in Göschenen", Zürich, 1899

Jacques E., Wauters P., (1999), "Improving the ventilation efficiency of jetfans in longitudinally ventilated rectangular ducts", Proceedings of the 8th US Mine Ventilation Symposium, ISBN 1-887009-04-3, University of Missouri-Rolla, pp.503-507

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

Kenrick, B. (2008), "Holmesdale Tunnel Saccardo System Commissioning", UK Road Tunnel Operators Forum, Fire Service College, March.

Martegani, A.D., Pavesi, G. and Barbetta, C. (2000), "Experimental investigation of interaction of plain jetfans mounted in series", 10th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Boston, USA, 1-3 November.

Marti, M., Brandt, R. (2004), "Strömungsmessung, Tunnel de Collembey", HBI report 03-100-02, 23 February 2004

PIARC (2008), "Road Tunnels: Operational Strategies for Emergency Ventilation", Technical Committee C3.3 Tunnel Operations, Working Group No. 6 Ventilation and Fire Control, World Road Association.

Pischinger, R. (2002), "Verfahren zur Beeinflussung der Tunnellängsströmung einer befahrbaren Tunnelröhre mit Querlüftung zur Verbesserung der Rauchgasabsaugung", Patent AT 411 919 B, Austria, DVR 0078018

Pospisil, P., Ilg, M., Marti, M. Brandt, R., "Messungen an der Tunnellüftungsanlage der Tunnels Balmenrain und Uznaberg, Hauptstrasse T8/A8", HBI Report 87-95-10, November 2003

Pruckmayer, G. Steinrück, H., Brandl, A. (2008), "Dimensioning of a fresh-air-impulse-damper", 4th international Conference on Tunnel Safety and Ventilation, 2008, Graz, ISBN: 978-3-85125-008-4

Rohne, E. (1964), "Über die Längslüftung von Autotunneln mit Strahlventilatoren", Schweizerische Bauzeitung, 82. Jahrgang, Heft 48, Seiten 840-844

Sturm, P.J., Bacher, M., Brandt, R. (2008), "Evolving needs of tunnel ventilation in a changing world", 4th international Conference on Tunnel Safety and Ventilation, 2008, Graz, ISBN: 978-3-85125-008-4

Tabarra, M., Matthews, R.D. and Kenrick, B.J. (2000), "The revival of Saccardo ejectors – history, fundamentals, and applications", 10th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Boston, USA, 1-3 November.

Tarada, F. (2008). 'Improved Tunnel Ventilation Device', United Kingdom Patent Application Number 0821278.9.

Truckenbrodt E. (1980), Fluidmechanik I, Springer.