ADJUSTABLE TUNNEL DAMPERS - AN ESSENTIAL COMPONENT FOR SMOKE-EXTRACTION DURING FIRES

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ABSTRACT

Requirements on tunnel ventilation systems (and thus on extraction dampers as well) have become markedly more stringent in the past years, due to increased knowledge and a great deal of experience. In Austria, these requirements (primarily leakproofing and temperature resistance) are defined by the applicable project-inspection directive RVS. However, aspects of flow technology, choice of materials, processing guidelines and experience in technical production must also be taken into account when conceiving, manufacturing and selecting extraction dampers.

As the European market’s leader in tunnel extraction dampers, Sirocco presents in the first part of this discussion a detailed, practically-oriented look at the way the requirements are met, indicating the essentials of an extraction damper.

During normal operation, the settable extraction damper’s suctioning (the aperture angle of which can be reset depending on the distance from the ventilator) is markedly technically advantageous in terms of flow (pulse effect). The pulse effects have been proved in comprehensive model testing, in which the resistance coefficient $\theta$ of an extraction damper was determined with respect to an aperture angle.

Key words: leakproofing, temperature resistance, stainless steel, pulse effect

1. INTRODUCTION

Modern concepts of transverse-ventilated roadway tunnels evince that extraction dampers built into the intermediate ceiling are an essential component for a ventilation system to function efficiently.

The great advantage of this ventilation concept lies in the fact that, in cases of fire, smoke-gases can be pinpointed and suctioned off in the vicinity of the fire. In ideal cases, this results in only a short section of the traffic area becoming filled with smoke, and fresh air flows to the fire location from both sides. Thus, the danger that tunnel users will be enveloped by smoke gases is markedly reduced.

Since, in this type of fire ventilation, smoke gases flow through the dampers unrarified, i.e. at a very high temperature, the dampers must be able to withstand very great temperature stress.

Furthermore, aiming for maximum suction performance during fire-ventilation operations requires that the extraction dampers be leakproof and facilitate flow.
2. TUNNEL DAMPER REQUIREMENTS

2.1. Requirements set out in the applicable project inspection directive RVS

The Austrian project inspection directive on tunnel ventilation equipment, decreed by the Federal Ministry of Transport, Innovation and Technology, was amended per January 2001 by Inspection RVS 9.261 after the fire in the Tauern tunnel and in the light of new knowledge gained in past years. This amendment imposes even more stringent requirements on ventilation equipment – and extraction dampers in particular – than were formerly the case with Austrian tunnel-ventilation units.

In cross-ventilated tunnels, the minimum extraction capacity was increased to 120m³/sec.; this extraction quantity must be attained in a section of 150 m at any point in the air duct.

In order to make this extraction quantity economically viable, the leakage requirements for air ducts and extraction dampers were markedly increased.

The following maximum allowable leakage values apply:

- air duct: 5 m³/sec km
- extraction dampers: 0.10 m³/sec m² at 2500 N/m²

Measuring data must confirm that both the shutters and the air duct are leakproof.

Extraction dampers must be designed to be as wide as possible (ideally, 3 m) and the total surface area of the cleared concrete openings for the dampers must be at least the same size as the air-duct surface at a length of 150 m.

For extraction ventilators, the requirements for temperature resistance were increased to 400° C during 60 minutes, implying that this minimum requirement for temperature resistance also applies to extraction dampers.

2.2. Materials and Processing

Due to the stringent requirement for temperature resistance (400° C) and the demand for functional safety over decades in extreme ambient conditions (exhaust gases, roadway salt, high dirt build-up), only top-quality stainless steels may be used to make extraction dampers.

The basic component in stainless steel corrosion resistance is a chrome conduct of at least 15%. At 18% chrome and 8% nickel, the steel becomes resistant to rust and acid, and by further adding molybdenum, it is resistant to holing caused by corrosion. Unfortunately, in practice it is not possible to use the optimally resistant steel, since – apart from the high cost of the material – it is no longer ductile if the molybdenum content is greater than 5%. Furthermore, the more the steel is alloyed, the less it can be welded.

Therefore, Stainless Steel 1.4571 (X 6 CrNiMoTi 17 12 2) has proved to be the best type for use in tunnel construction.

In order to keep the Stainless Steel 1.4571 corrosion-resistant and impervious to pitting, the engineering rules corresponding to construction and processing directives must unconditionally be taken into account (cf. also Quality Standard DIN 8563; EN 25817); otherwise, the steel will not be corrosion-resistant and functional safety cannot be guaranteed.

The two essential stainless-steel processing rules are:

- All weld seams are to be made continuously and on both sides, without exception. Tack and spot welding are not permissible, since they inevitably entail corrosion because, on the one hand, no passive layer can form in the narrow gaps around a weld.
seam and, on the other hand, subsequent mordant treatment and passivation are not possible (the acid used for mordant treatment cannot be removed without a trace from the gaps).

- All welded parts, just as all parts tooled with non-stainless utensils, must be given mordant treatment after processing to clean them, following which they must be protected by passivation (passive layer build-up on the metal’s surface). If the passive layer has been damaged chemically or mechanically, local corrosion develops.

Of course, complying with the processing rules involves expense, some of which is not inconsiderable. Mordant treatment and passivation by qualified companies alone is time-consuming (reacting duration) and cost-intensive (approx. 7% of total manufacturing costs).

However, it is mandatory that the applicable regulations, standards and necessary quality requirements be observed without compromise.

2.3. Flow-Technical Requirements

During normal ventilating operation, the extraction dampers must be set so that smooth suctioning is assured throughout the entire tunnel. This means that, the closer the dampers are to the exhaust ventilator, the smaller the aperture angles of the vanes (free cross-section surface) are.

In order to ensure that this is so and, simultaneously, to assure the best possible flow even at small aperture angles, the following points must be taken into account:

- vanes must run equally (pulse effect)
- mechanical and electrical hysteresis when starting up intermediate positions must not exceed 1%
- small aperture angles must be capable of being set stably. This means that there must be only very little vane (and rod assembly) play
- vane geometry should be favourable to flow even at small aperture angles and produce the least possible whistling noise, even at high flow speeds, by using rigid, stable vane-ends

In general, one should strive for low resistance, minimal reduction of cross-sectional surface in the exhaust duct and construction favourable to flow.

Major flow-technical characteristics:

- Extraction dampers should be built into the intermediate ceiling and, when closed, protrude into the exhaust duct as little as possible.
- All parts which protrude into the exhaust duct must be panelled with flow-past profiles.
- On the roadway side, the extraction dampers should be outfitted with inflow nozzles, in order to reduce the resistance coefficient.
- Vane geometry should be favourable to flow (low resistance coefficient).
3. DEVELOPING AN EXTRACTION DAMPER WHICH CONFORMS TO REQUIREMENTS

Together with leading tunnel planners and building firms, the Austrian Sirocco Company has been working for decades on improving tunnel ventilation systems. For more than 20 years now, Sirocco has been involved in developing and producing stainless steel extraction dampers. The result of these years of experience is a high-quality product which conforms to all requirements and which has made Sirocco the market-leader. The essential characteristics of Sirocco extraction dampers are described below.

3.1. Flow favourability

The fish-belly vane developed by Sirocco has been optimised according to flow-technical standpoints, the result of which is, on the one hand, only slight cross-sectional narrowing when the damper is open and, on the other, efficient, flow-through of the vanes, low in both resistance and turbulence. Both of these features assure improved suction performance in cases of emergency. In the course of this development, the vanes’ overlapping ends were designed so that labyrinth-sealing occurs when they are closed.

3.2. Leakage prevention

The stringent requirements for preventing leakage and the simultaneous demand for temperature resistance can only be met by using metal sealing systems. Furthermore, they must be impervious to dirt, corrosion-resistant and must maintain their sealing effect permanently.

The sealing system developed at Sirocco fulfils these criteria.

A springing seal is placed on every damper vane (Fig. 3), which covers the gap (necessary for thermal expansion) between the vane and the frame, thereby assuring a high degree of sealing, both during normal operation and in cases of fire alike. By bending the closed vanes through under high partial-vacuum air pressure of approx. 4000 Pa, gaps occur on the first and last vane between the rabbet and the bent-through vanes. The new rabbet (Fig. 4), protected throughout Europe, seals this variable gap, corrosion-free and with no wear and tear.
3.3. 400° C temperature resistance

Not only must stringent temperature requirements (400° C/60 min.) be taken into account when selecting the materials to be used (temperature resistance, solidity), but they also demand targeted construction procedures.

In order to ensure that the dampers function under temperature, the individual components’ varying longitudinal expansion must be considered, with the following results:

- the entire damper must be capable of expansion in the concrete cut-out; it must not be rigidly connected to the concrete. Therefore, Sirocco dampers are fastened (clamped) to the concrete with U-bolts; they can expand when temperature-stressed.
- The vanes, surrounded by flowing smoke gases, heat up markedly sooner than the vane frame. Here, relative temperature difference between the vanes and the shutter frame must be taken into account by the use of sufficient gaps, so that the vanes remain mobile under temperature.
- Correct functioning under temperature influence should be obligatorily evidenced in a fire-test through cyclic opening and closing. Furthermore, fire-testing should include optical checking (light gap) of whether the vanes are completely shut when in the closed position.
- In general, the start-up motor is outfitted with an electronic control unit, which results in a maximal permissible temperature stress of 80° C. Thus, the drive must be thermally protected against hot smoke gases. There are two options: If a separate air-feed duct is available, the drive is installed in the cold air-feed duct and connected with the extraction damper via a drive shaft. It is essential at this point that, on the one hand, the wall-piercing (drill-hole) is thermally (and, of course, hermetically) bulkheaded and, on the other hand, that the drive shaft is outfitted with a thermal coupler.
  If the drive has to be installed in the exhaust duct, a thermal casing is mandatory. For physical reasons, such a casing can only keep temperature away from the drive for a limited time. Sirocco has developed a stainless-steel casing lined with various insulating materials separated by air cushions and certified for 400° C / 90 min.

As a general rule, more stringent the extraction dampers’ temperature requirements, the more complex it will be to achieve optimal leakage prevention. Sirocco extraction dampers have been fire-prevention certified (400° C/120 min.); the certificate also covers function-testing under temperature and visual checking for leakage. In addition, Sirocco has its own certified
leakage-testing shop, where extraction dampers can be tested and optimised up to dimensions of 4.0 m x 3.0 m.

4. TECHNICAL ASPECTS OF VENTILATION

4.1 Concentrated smoke suctioning

We now come to the question, „Why are extraction dampers and ventilator cowls needed in the first place?“ Isn’t it enough to have large openings in the intermediate ceiling in cross-ventilated or semi-cross-ventilated tunnels to suction off smoke in a case of fire?

In Fig. 5, you can see a schematic rendering of an extraction duct, with the intermediate ceiling and the traffic area below. There are openings of the same size at specific intervals in the ceiling. An exhaust ventilator is indicated at the end of the extraction duct; the ventilator suctions off exhaust out of the extraction duct. When the ventilator is switched on, the exhaust is distributed as shown here, due to local pressure conditions. \( S_A \) is the dimensionless suction volume, that is, the ratio of local suction volume to the mean value, and \( \xi \) is the dimensionless duct length, that is, the ratio of the running length to the duct length. You can see that a large quantity is suctioned off in the ventilator’s vicinity, whereas very little is suctioned at the end of the extraction duct. However, during normal operation (especially at full load), it is necessary to assure smooth exhaust suctioning (i.e. \( S_A = 1 \)) throughout the duct’s entire length, since otherwise high concentration peaks can occur in the tunnel. Smooth suctioning can be achieved by mounting chokers, that is, ventilator cowls and/or extraction dampers at each opening. Near the ventilator, this choking must be very great, whereas it need only be very slight at the end of the exhaust duct, in order to achieve smooth suctioning.

Bear in mind, however, that every choking is a loss of pressure which must be compensated by the exhaust ventilator, and entails more expense when operating the ventilating equipment. Pressure loss in the exhaust openings is absolutely necessary to achieve smooth exhaust suctioning; thus, it cannot be reduced. On the other hand, pressure loss in the exhaust duct must be kept to a minimum. This is why it is necessary to fully exploit the inflow pulse of the exhaust, that is, the exhaust must be fed into the duct at a very small angle. Pure choking of the inflowing exhaust without using the inflow pulse – as shown in Fig. 6 – leads to large pressures losses in the exhaust duct and to high costs of operating the ventilation equipment.
During fire operation, an extraction damper near the fire’s location is opened fully, whereas all the others are shut tight. This allows the greatest possible volume of smoke gas to be suctioned off through the open extraction damper. The ventilator’s entire suction effect is concentrated on the area of the fire, where $s_A$ is very large; by contrast, it is zero throughout the rest of the duct.

Optimal aerodynamic designing of the extraction dampers ensures a large suctioning volume. This begins as early as the stage of determining the size of the concrete openings for the extraction dampers. They should be large enough so that the flow speed in the open damper is not much larger than in the cross-section of the exhaust duct. In significantly smaller openings, the flow is initially greatly accelerated, which means it must be strongly detained in the exhaust duct which, in turn, leads to major losses of pressure.

4.2 Theoretical calculations

Thus, there are three ducts in cross-ventilating (traffic area, exhaust duct, air-feed duct) and two interconnection openings, viz. the extraction dampers and the fresh-air blower. Therefore, the pressure progression in the exhaust duct and the traffic area are also influenced by the flow conditions in the air-feed duct. This results in a very complicated system of equations – six paired, non-linear differential equations – for the progressions of pressure and speed in the individual ducts.

Here, for instance, you can see the differential calculations for the progressions of pressure and speed in the traffic area (equations 1 and 2).

**Equation 1**

$$\frac{dp}{dx} = -\kappa_1 \cdot \frac{1}{D_1} \cdot \rho \cdot \frac{u^2}{2} \cdot \text{sign}(u) - \rho \cdot \frac{du}{dx} \cdot \frac{u}{2} - k_1 \cdot \frac{F_1}{\Delta_1} \cdot \left( \frac{u_i u}{u_j} \cdot \frac{\Delta_1}{\Delta_2} \cdot (u_i + u_j) \right) \cdot \text{sign}(u_i + u_j)$$

**Equation 2**

$$\frac{du}{dx} = -\frac{1}{F_1} \left( F_1 \cdot \frac{du}{dx} + F_2 \cdot \frac{du}{dx} \right)$$

Equations 3 and 4 show the progression of pressure and speed for the fresh-air duct.

**Equation 3**

$$\frac{dp}{dx} = -\kappa_3 \cdot \frac{1}{D_3} \cdot \rho \cdot \frac{u^2}{2} \cdot \text{sign}(u) - \rho \cdot \frac{du}{dx} \cdot \frac{u}{2}$$

**Equation 4**

$$\frac{du}{dx} = -\frac{1}{F_3} \cdot \frac{F_3}{\sqrt{\Delta_3}} \cdot \left( \frac{1}{\Delta_3} \cdot \sum_{i=1}^{n} \Delta_i \cdot \frac{u_i}{u_j} \right)$$

Equations 5 and 6 show the progressions of pressure and speed for the exhaust duct.

**Equation 5**

$$\frac{dp}{dx} = -\kappa_5 \cdot \frac{1}{D_5} \cdot \rho \cdot \frac{u^2}{2} \cdot \text{sign}(u) - \rho \cdot \frac{du}{dx} \cdot \frac{u}{2}$$

**Equation 6**

$$\frac{du}{dx} = -\frac{1}{F_5} \cdot \frac{F_5}{\sqrt{\Delta_5}} \cdot \left( \frac{1}{\Delta_5} \cdot \sum_{i=1}^{m} \Delta_i \cdot \frac{u_i}{u_j} \right)$$

This entire system of equations must be solved numerically, taking marginal values into account.
For example; the progression of pressure in an exhaust duct 1370 metres long was calculated for normal operation, if the exhaust is suctioned vertically into the exhaust duct without exploiting pulse ($\alpha = 90^\circ$). The partial vacuum at the end of the duct amounts to 1100 N/m$^2$.

By contrast, if the exhaust is fed into the exhaust duct in the flow direction ($\alpha = \sim 0^\circ$) and the pulse is fully exploited, the partial vacuum at the end of the duct is only 650 N/m$^2$. At a maximum exhaust volume of 110 m$^3$/s, this results in increased exhaust ventilator output of 70 kW in a tunnel 1375 metres long, without exploiting inflow pulse.

### 4.3 Model testing

The Sirocco company commissioned model tests in order to achieve the most favourable flow conditions in a case of fire at a fully-opened extraction damper in the Plabutsch tunnel. Testing was conducted with the authorisation of the Office of the Styrian Provincial Government in the tunnel’s winch house.

In Fig. 8, you can see the model of the exhaust duct, approx. 15 metres long. The exhaust duct, modelled in wood construction, is at the front, and the exhaust ventilator’s drive-motor and the soundproofing are visible in the background.

Pressure losses in the extraction damper were calculated at four different vane angles, $\alpha = 60^\circ$, $\alpha = 75^\circ$, $\alpha = 90^\circ$ and $\alpha = 115^\circ$ in the exhaust duct, thereby determining the resistance coefficient $\zeta$ (zeta) for the entire inflow.

Fig. 9 shows the results of measuring. We can see that the lowest resistance coefficient is achieved ($\zeta = 1.3$) at an inflow angle of $\alpha = 90^\circ$. Although less exhaust flows into the traffic area at smaller inflow angles, a certain amount of pressure is recovered through the inflow pulse aimed in the direction of the exhaust duct; however, the resistance coefficient is higher than at $\alpha = 90^\circ$. But if the exhaust is suctioned in the direction opposite to that of the flow ($\alpha = 105^\circ$), the negatively aimed inflow pulse leads to additional drop in pressure in the exhaust duct, which sharply increases the resistance coefficient.

After measuring, the vanes and the central stay were taken out of the extraction damper, so that only the large non-sporulated exhaust opening remained, as it appears with an exhaust slide-gate. Measurements showed that the resistance coefficient of the unchoked opening is about 2.7, that is, it was larger than the coefficient of a fully-opened extraction damper.