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Development and state of the art in road tunnel ventilation technology

Until the 1950s, traffic densities were very low compared to today's levels and environmental aspects were a minor issue at best.

Subsequent economic growth brought a progressive year-by-year increase in individual transport volumes (transit, vacation travel, commuting). The resulting traffic congestion in conurbated areas and Alpine regions gave rise to pollutant emission levels that soon exceeded the tolerance thresholds of motorists and local residents.

This situation forced public authorities to take a hard look at traffic densities and to identify solutions that would ensure the environmental sustainability of anticipated future concentrations.

Tunnel systems emerged as the solution of choice. Europe, with its high population densities, soon acquired cutting-edge expertise in tunnel technology.

The length of vehicular tunnels varied between 3 and 16 kilometers at that time. To ventilate such long tunnel sections, planners - and, ultimately, building contractors - had to undertake pioneering work since experience with older tunnel systems in other parts of the world was scarce and not easily adaptable to the challenges encountered.

In those days, the development of individual components for tunnel ventilation equipment proceeded concurrently with the development of fans for thermal power plants, mine ventilation systems, and wind tunnels for aerodynamic testing applications.

With many components, development projects and trial results could be directly transferred to tunnel ventilation applications. The high level of tunnel ventilation technology attained today is ultimately a direct outcome of this synergy effect.

A major unknown quantity was the development of future traffic densities and, in the final analysis, the growth in vehicle exhaust emissions in the period leading up to 2000.

At that time, CO emissions and opacity had already been identified as key parameters for determining the fresh-air demand of tunnel systems. In addition, traffic volumes by the year 2000 had been extrapolated from the rapid growth of the '60s and '70s. These calculations yielded high fresh-air demand levels which, as we know today, were far overestimated since progress in automotive technology could not be forecast with any degree of accuracy.

The first tunnel systems were typically projected with semi-transverse ventilation (Diagram 1) for medium tunnel lengths and full transverse ventilation (Diagram 2) for long tunnels. A combination of both systems was likewise employed later.

Fig. 1: Tunnel entry / exit portal

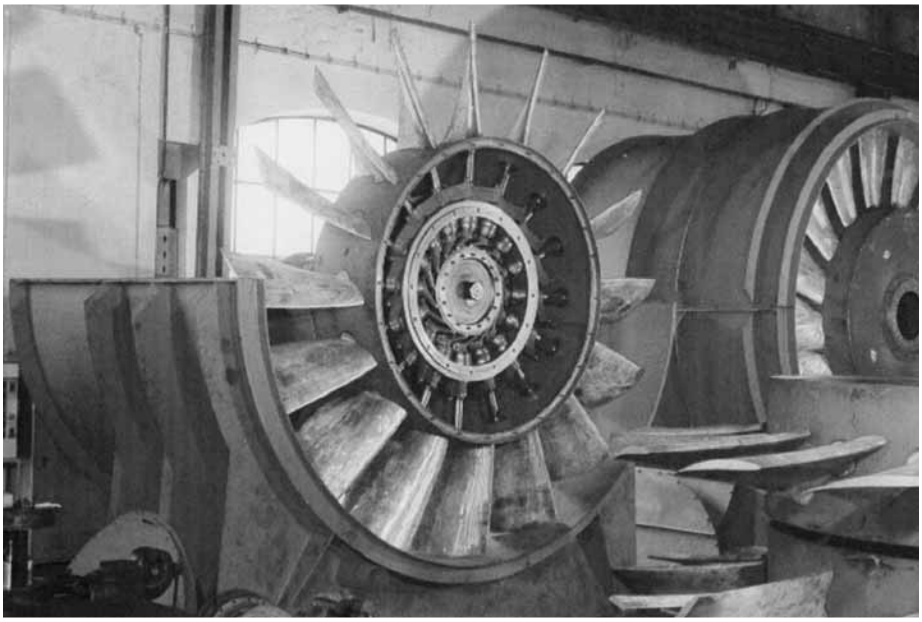

Fig. 2: Axial-flow fan with hydraulic impeller blade pitch adjustment

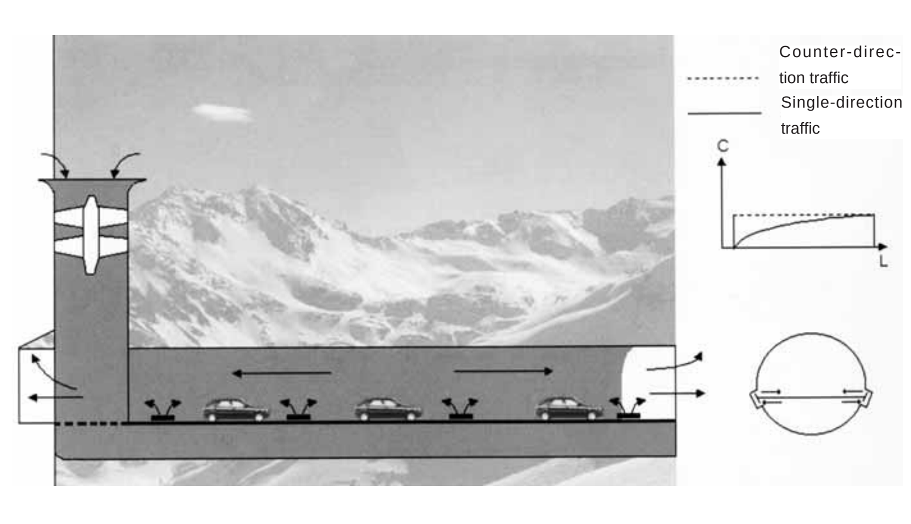

Diagram 1: Semi-transverse ventilation

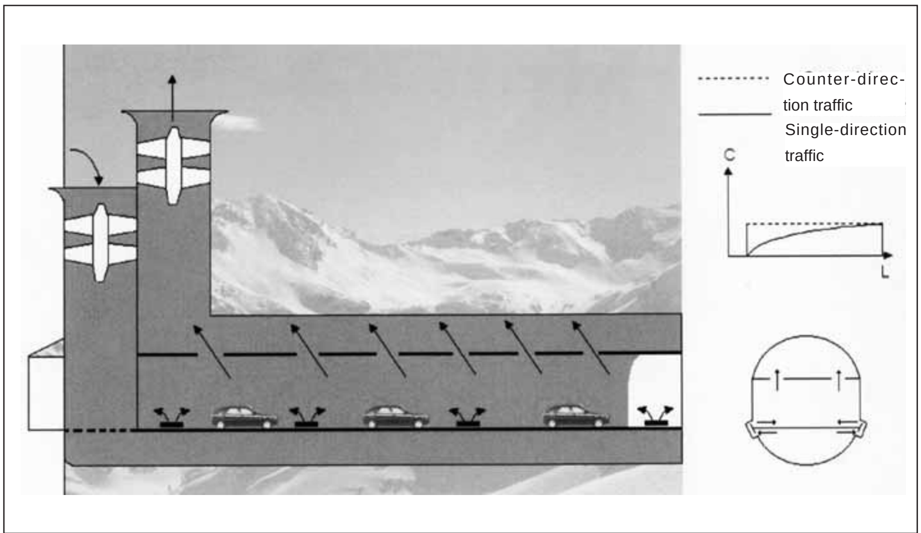

Diagram 2: Fully-transverse ventilation

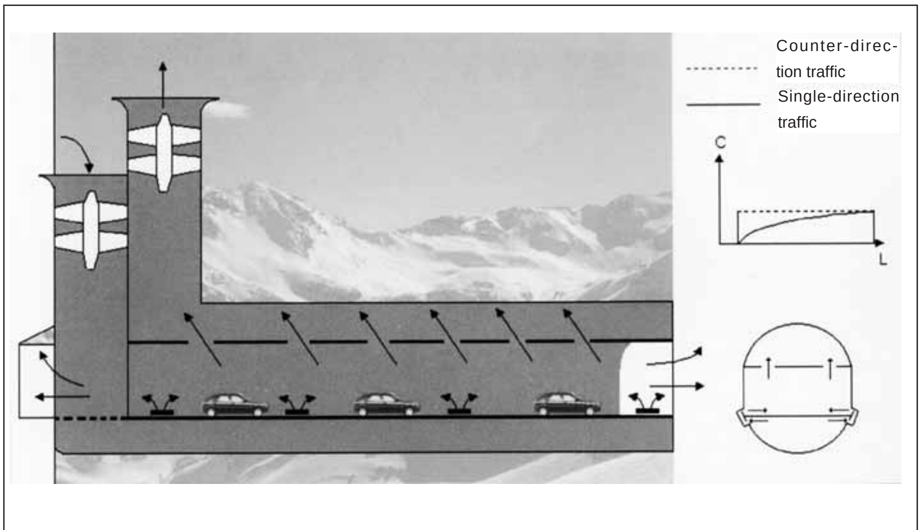

Diagram 3:Combined semi-/fully-transverse ventilation

The broad fan control ranges required could only be implemented in an economically efficient manner by combining variable-flow fan designs using "on-line" blade pitch adjustment with multiple fixed rpm stages.

Semi-transverse ventilation using axial-flow fans

As a general rule, semi-transverse ventilation systems introduce just enough fresh air into the tunnel to dilute the emitted pollutant loads. Thus diluted, the tunnel air exits from both portals in equal proportions.

A controlled flow of fresh air is introduced continuously into a separate air duct from which the requisite partial volumes are forced into the roadway tunnel via so-called secondary ducts.

To ensure that the direction of flow can be controlled in the case of a fire, reversible axial-flow fan systems are employed. Under normal conditions these units operate as supply fans. If necessary they can be switched to exhaust mode, extracting air via the secondary ducts.

Compared with longitudinal venting using jet fans, such systems offer the advantage of producing lower longitudinal airflow velocities since the air can exit through both portals. Semi-transverse ventilation is therefore viable for longer road tunnels as well. On the other hand, the cross-section of the tube may be reduced by the inevitable supply air ducting. As a result, the longitudinal air velocity may be reduced compared to longitudinal venting.

Fully transverse ventilation using centrifugal fans

With fully transverse ventilation, fresh air is supplied to each point of the roadway in exactly the extracted quantity.

Fresh air is introduced into distribution ducts extending along each tube's length and blown into the tunnel through air-supply openings (so-called secondary ducts).

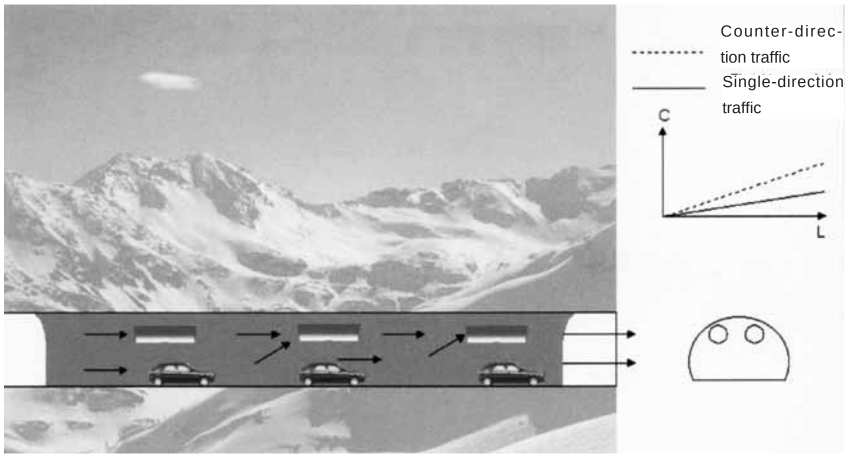

Diagram 4: Longitudinal ventilation using jet fans

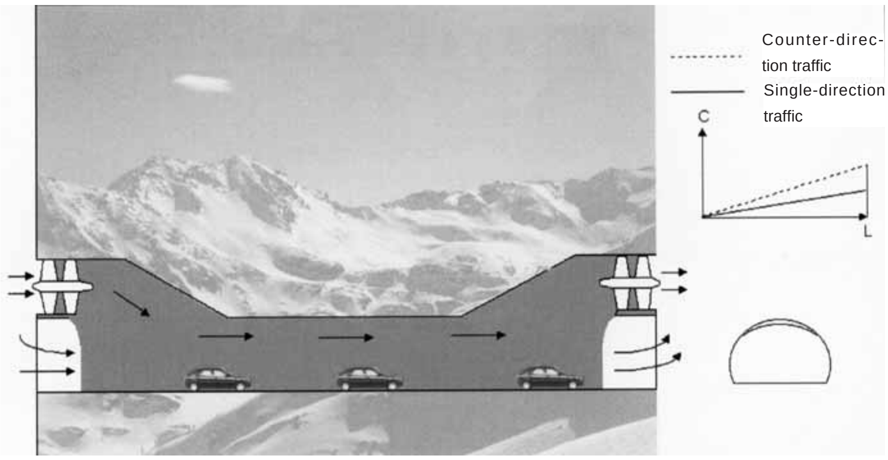

Diagram 5: Longitudinal ventilation using Saccardo nozzles

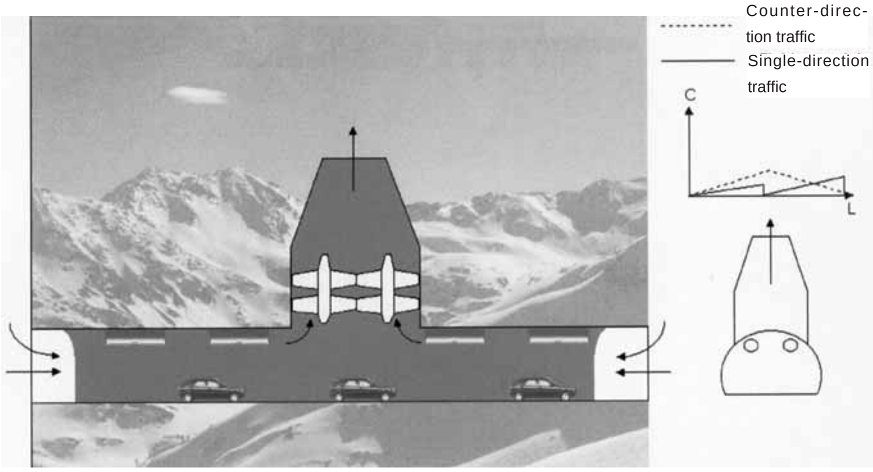

Diagram 6: Longitudinal ventilation using exhaust air fans

The exhaust air carrying pollutant loads is continuously extracted over the length of the tunnel via so-called exhaust vents. The individual exhaust air flows are combined in plenums running parallel to the tunnel, then discharged via exhaust stacks.

In one variant of the fully transverse ventilation method, referred to as “reduced transverse ventilation”, the rated exhaust air flows are smaller than the supply-air volume. The excess of air leaves the tunnel via the portals (Diagram 3).

Forced ventilation

In recent years, a clear trend towards longitudinal ventilation has emerged for medium tunnel lengths of up to 3 kilometers.

The success of this ventilation method is partly attributable to the lower capital outlay, operating overhead and maintenance cost involved.

Jet fans arranged individually or in groups (Diagram 4) at specified distances along the tunnel’s roof impart energy pulses to the air column, thus inducing airflow movement.. With this design, care must be taken in determining fan spacings along the tunnel axis to ensure good intermixing of the jet discharge and the remaining tunnel airflow, as well as an optimum flow distribution across the tube.

The length of jet fan ventilated tunnels is limited by the maximum longitudinal air velocity, since the speed of the airflow must not exceed accepted safety and comfort levels. For the sake of completeness, the longitudinal air management method based on Saccardo nozzles should likewise be mentioned here.

Saccardo nozzles (Diagram 5) are fed by axial-flow fans mounted at the tunnel portal. The nozzle injects the fan intake into the roadway tube at a 15 to 20-degree angle to the tunnel axis and air speeds between 25 and 30 m/sec via a circular gap in the upper portal area.

However, this ventilation method has been found fairly sensitive to changes in airflow resistance, regardless of cause (e.g., wind). It is therefore no longer considered in newer installations. Another interesting recent development in longitudinal road ventilation is the use of exhaust air fans mounted in caverns and operating via central ducting (Diagram 6).

In this system, fresh air is drawn in from both portals by large axial-flow fans arranged in caverns near the middle of the tunnel. Exhaust air is extracted and discharged via an outlet shaft. A benefit of this system lies in the fact that no exhaust air exits from the portals and that the length of the ventilation air-way is virtually reduced by half, with attendant advantageous effects on tunnel CO and opacity levels. It is often combined with additional jet fans inside the tunnel which are activated in the case of a fire to keep escape routes clear of smoke.

Irrespective of the foregoing, the other ventilation techniques, viz.

- reduced semi-transverse ventilation
- semi-transverse ventilation
- fully transverse ventilation

each have their own specific advantages over all-longitudinal ventilation in terms of fire safety, ride comfort and environmental compatibility and will therefore be adopted or specified on a case-by-case basis. Needless to say, combinations between longitudinal and semi-transverse ventilation may be found effective both under normal operating conditions and in the event of a fire.

Modern selection criteria for ventilation systems

The choice of a tunnel ventilation system is essentially determined by the following factors:

- fresh-air demand as a function of CO, NOx and opacity-inducing emissions, taking into account legal requirements and the anticipated trend in emission levels and control thresholds over the next few years (current data are prescribed in RABT and PIARC guidelines);
- reliability of the system;

Fig. 3: Jet fan during manufacture, powder coated and with closed impeller (impeller hub sealed off against dust and corrosion)

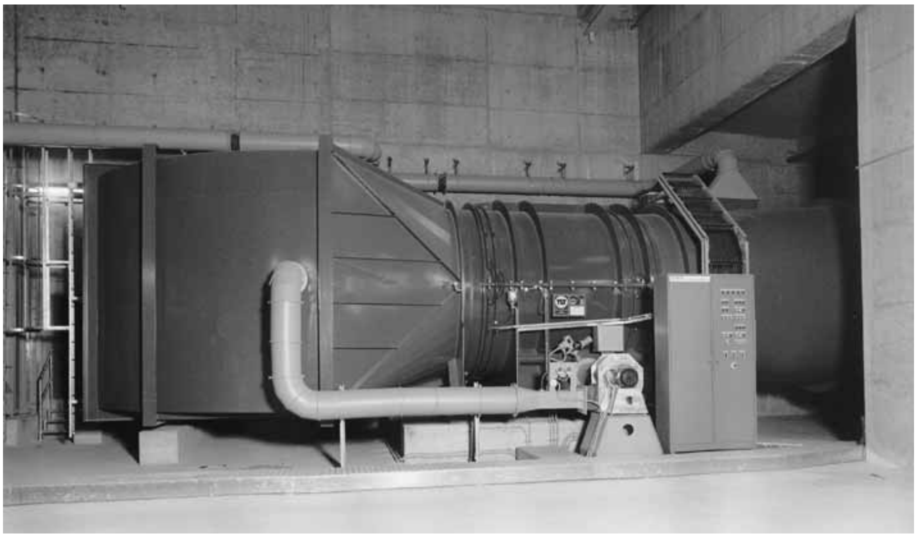

Fig. 4: Axial-flow exhaust fan

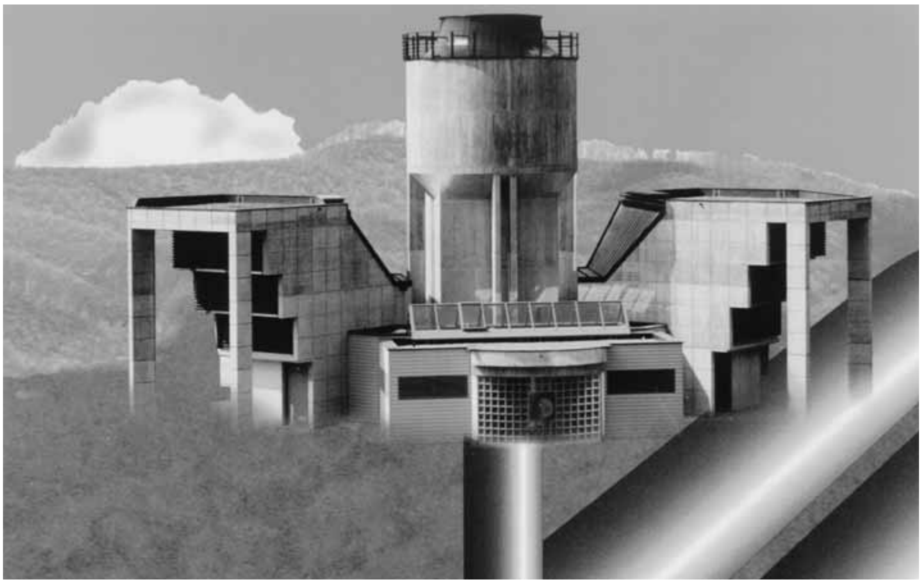

Fig. 5: Operating building with outlet shaft

- safety in the case of a fire;
- energy consumption;
- investment cost;
- maintenance;
- service friendliness.

Control systems

Each fan control concept must be aligned with the demands of the tunnel ventilation system.

To meet specified immission thresholds inside the tunnel and with regard to the overall environment, fresh-air and exhaust flow rates have to be continuously adapted to the current traffic load. The following flow control methods are used:

Longitudinal ventilation using jet fans: activation and de-activation of individual fans or fan groups over the length of the tunnel.

Longitudinal ventilation using exhaust stacks in tunnel caverns / semi-transverse or transverse ventilation of longer tunnels using axial-flow fresh-air and exhaust fans at the tunnel portals or in tunnel caverns:

Here the following control options are employed:

(Chart 1): Impeller blade pitch angle adjustment during operation, combined with one or more fixed motor rpm stages (via pole-changing motors)

(Chart 2): Speed-controlled fans with individual impeller blade pitch angle adjustment on the stationary fan and variable-speed inverter control.

Both control methods have proven their merits in practice. The use of one or the other method will depend on the intended operating conditions, which are often associated with different system airflow resistance characteristics.

In a ventilation system with a square-law airflow resistance graph, both "on-line" blade pitch adjustment and rpm control are viable control strategies.

Problems will often arise if different airflow resistance characteristics are

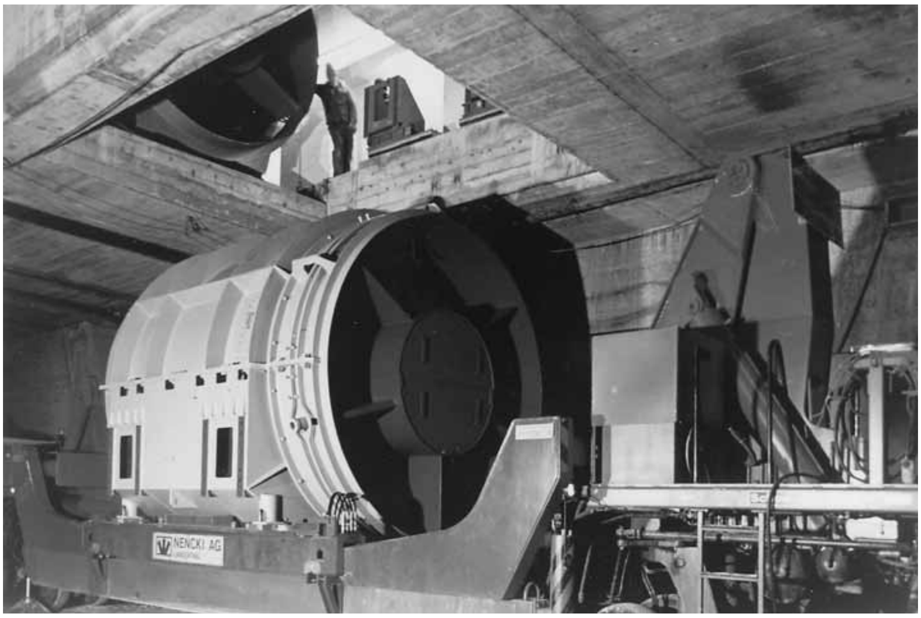

Fig. 6: Axial-flow fan during installation in the fan house

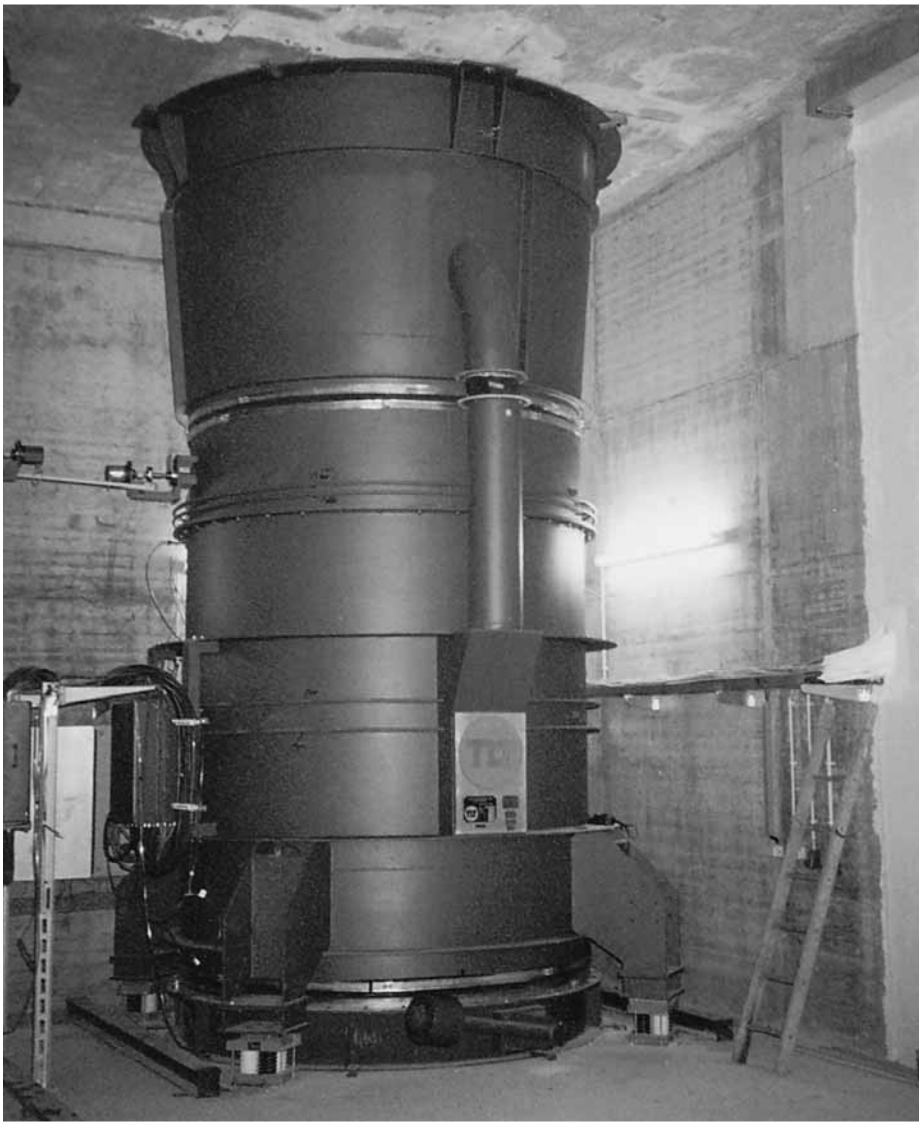

Fig. 7: Upright reversible axial-flow fan

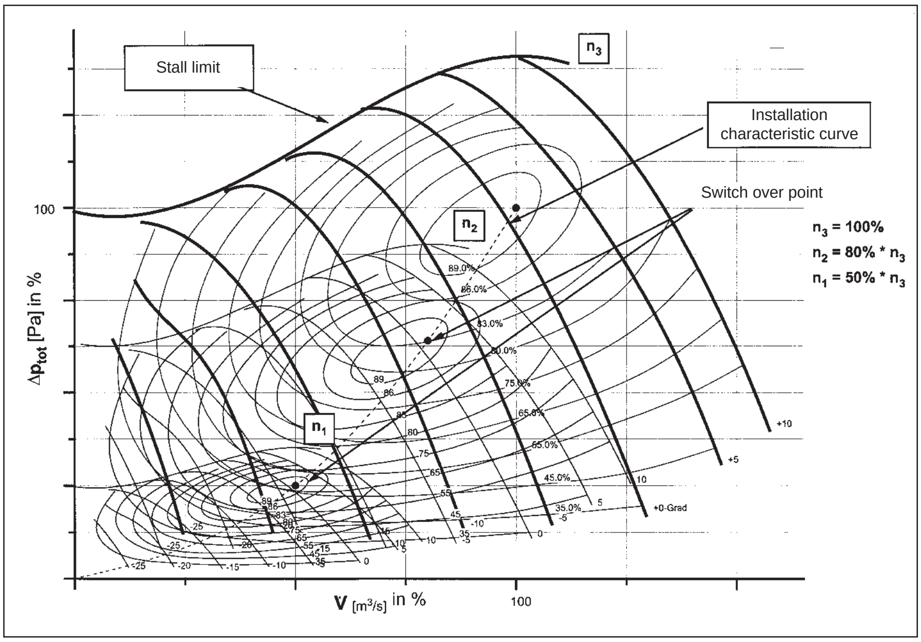

Chart 1: Characteristic curves of an axial-flow fan with hydraulic impeller blade pitch adjustment

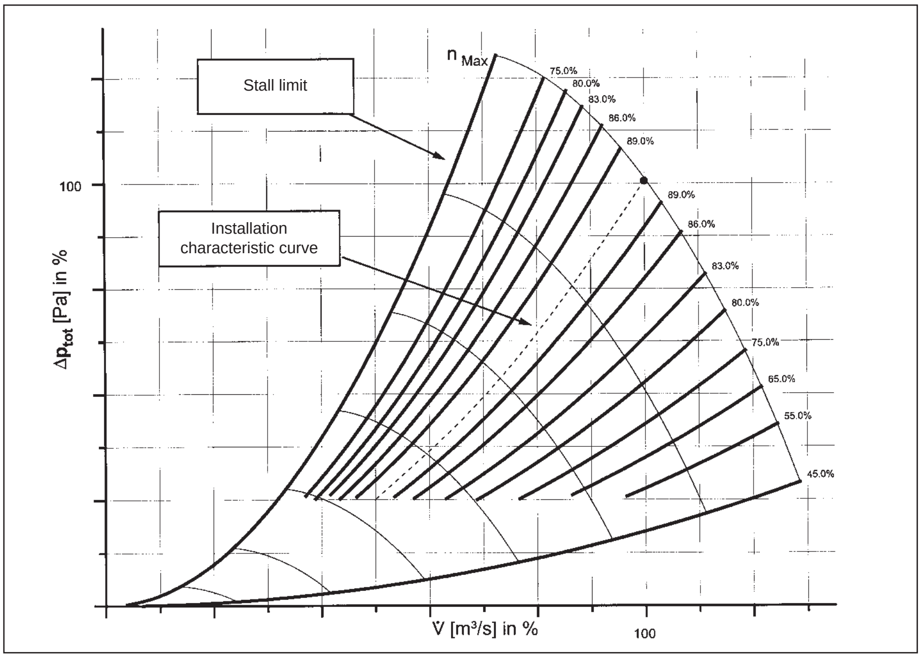

Chart 2: Characteristic curves of an axial-flow fan with rpm control based on a frequency converter

encountered in different ventilation modes (e.g., during reverse operation of the ventilating system in the case of a fire).

The duct resistances in normal and reverse operation change with the inlet and outlet conditions at individual components. In addition, deflection effects caused by the damper system may result in highly inhomogeneous losses and hence, different tunnel resistance characteristics.

Both operating extremes must be known as early as in the project phase (i.e., when the control concept is determined) and must be taken into account in the fan design and rating process.

In a speed-controlled system, the stall limit for a given fixed blade position describes a parabolic curve through the origin.

In any case, care must be taken to keep all operating points at a safe distance from the fan's speed-related stall line. To meet this requirement, compromises will often have to be made in selecting the position of these points relative to the optimum efficiency level between the "normal operation" and "fire" operating ranges.

On fans with "on-line" impeller pitch control, such restrictions will not normally apply due to the favourable course of the fan's stall limit line relative to the zero flow level.

A fan's so-called "holding pressure" at zero output flow is usually equal to between 50 and 60% of the maximum pressure. From this we may generalize that all operating points down to part-load mode (usually 10% of V.max) can be run safely without instability.

Another important aspect in selecting the control concept is the so-called "tunnel bias pressure" to be created at the appropriate inlet and exhaust vents under the various supply and extraction conditions so as to avoid uncontrolled flow reversals over the tunnel's length.

This so-called tunnel bias pressure shifts the tunnel's airflow resistance graph from zero to a negative or positive pressure. Positive bias is particularly critical.

With speed-controlled fans, frequent intersection with the stall line (parabolic curve through zero) in the part-load range imposes limits on the achievable minimum fan load.

The frequently voiced demand for 100 to 10% variability of the volume flow may not be attainable due to this intersection effect (black area in Chart 3). Here, too, variable-pitch fans offer performance benefits since these intersection problems do not occur.

For tunnel systems with fans operating at high rates of capacity utilization, a mixture of the two control systems may be advantageous. A combination of rpm control and hydraulic blade pitch adjustment can yield opti-

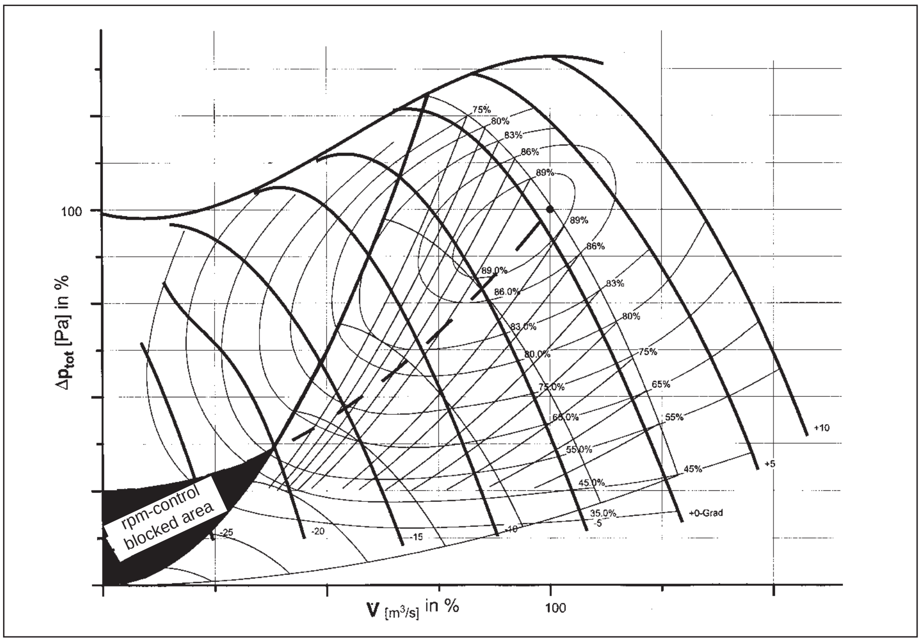

Chart 3: Characteristic curves of an axial-flow fan with hydraulic impeller blade pitch adjustment, superimposed by rpm control curves

mum energy efficiencies in day-to-day operation. The disadvantage is, that higher equipment cost will be incurred. However, the extra capital outlay may soon be reuperated by operating cost savings.

Fire safety

Exhaust air fans are generally required to remain operable for 1 hour max. at temperatures up to 250°C in the event of a fire. All components, including the fan motor unit, must conform to this specification.

In the case of exhaust air fans, the above imposes specific design requirements aimed at ensuring system safety, e.g.,

- high temperature resistant impeller blade materials;

- sophisticated, proven pitch adjustment systems which allow the impeller blade angles to be changed on the rotating fan and will not require increased actuating forces or become blocked altogether at elevated temperatures;

- drive motors with special cooling systems, with or without external cooling fans (depending on the selected motor protection class, e.g., IP 23 or IP 44 for open-circuit ventilated machines or IP 54 for totally enclosed fan cooled units).

Summary and outlook

Because of continuously improving pollutant emission values for new car generations, fire safety objectives will increasingly become the first and foremost consideration in tunnel ventilation design.

Exhaust fans removing smoke directly from the tunnel tube must be rated to withstand temperatures of at least 400°C for 90 minutes or more (RABT 94).

Literature:

RABT: Road Tunnel Equipment and Operating Guidelines

PIARC (Permanent International Association of Road Congresses) / AIPCR: Road Tunnels: Emission, Ventilation, Environment, Montreal 1995

1995 Zagreb Tunnel Convention, Paper delivered by Mr. W. Müller in Zagreb