TUNNEL CONSTRUCTION SITE VENTILATION AND COOLING: AN INTEGRATED FLOW AND HEAT LOAD SOLVER APPLIED TO THE LYON-TURIN HIGH-SPEED RAILROAD TUNNEL PROJECT

Uwe Drost, Marco Bettelini, INELMEC SA, Switzerland

ABSTRACT

Ventilation is required during the construction of any tunnel. This is true whether the tunnel is constructed by blasting, boring or placing prefabricated tubes in a trench. Temporary ventilation is necessary to provide a suitable, safe working environment for the construction workers. Since many flammable or airborne toxic gases, dust mist and fumes are released during the construction process, these contaminants can only be removed by ventilation. A dedicated, well-tailored ventilation system is compulsory in the presence of natural gas in terms of flammability and asbestos in terms of toxicity.
Ventilation systems for construction sites must be flexible in order to grow and move with the construction progress. They may therefore imply rather complex flow pattern including leakage flows, booster stations, filtering and cooling devices, conjunctions and disjunctions etc.

Depending on the excavation length and method as well as the geothermal and ambient boundary conditions, cooling of the working environment may also be required. Considerable heat may be transferred to the tunnel air from the rock mass, from the boring machine, other machinery and vehicles as well as from cement setting. Especially heat transfer from the rock-mass is complex, because it is transient in time due to the gradual cool-down of the rock from the tunnel wall.

Three major construction ventilation schemes are typically applied:

- forced ventilation employing flexible ducts to introduce fresh air directly to the work sites.
- exhaust ventilation sucking consumed and loaded air out of the tunnel employing reinforced flexible ducts or spiral steel ducts.
- circulation ventilation schemes being mainly used in double bore projects, where fresh air is introduced via one bore and consumed air is extracted via the second.

Obviously, combinations of these schemes are also often used in dependency of the local requirements.
The actual choice of the ventilation system for a specific site depends on one hand on the complexity of the project (excavation length and diameter, single or double bore, cooling requirements, intermediate multifunction stations, etc) and on the other hand on the national or local legislation, directives, codes and guidelines, which may differ largely from one country to another.

An integrated flow and heat transfer design tool capable to resolve all of the above described ventilation schemes is presented in the present paper. Examples are outlined and results of the construction site ventilation and cooling design for the Lyon-Turin high-speed railroad system are presented to illustrate the tools capacity.

NOMENCLATURE

A	m^2	cross section
Bi	-	Biot number
C_p	J/(kg K)	thermal capacity
D	m	diameter
f*	m^2/m^2	active leakage area
Fo	-	Fourrier number
g	-	usage factor
k	W/(m K)	thermal conductivity
M	kg/s	mass flow
Nu	-	Nusselt number
p	Pa	total pressure
P	kW	power Diesel engines
Pr	-	Prandtl number
Q	W	heat flux
R	m	radius
Re	-	Reynolds number
t	s	time
t	m	thickness
S	m^2	surface
T	°C	temperature
u	m/s	speed
U	W/m^2K	total thermal resistance
V	m^3/s	volume flow
x	m	distance
α	$W/(m^2 K)$	convection coefficient
Λ	m^2/s	thermal diffusivity
η	-	efficiency
λ	-	friction coefficient
ρ	kg/m^3	density
ζ	-	pressure loss coefficient

INTRODUCTION

The main aspects, which need to be considered for an appropriate design of a tunnel construction site ventilation and cooling system, are:

- Removal of the pollutants (exhaust gases of the vehicles, blasting fume, dust).
- Establishment and maintenance of a climatic state (temperature, humidity) in accordance with the required physical activities of the work force in the underground construction sites.

The main sources of heat release, which are typically encountered, are fourfold:

- The rock mass and the tunnel walls.
- The tunnel-boring machine.
- The vehicles and other motorized equipment.
- The cement.

For important current railway tunnel projects in Europe, namely

- Lötschberg base tunnel
- Gotthard base tunnel
- Lyon-Turin base tunnel (LTF)

the depth of coverage reaches values beyond 1’500-2’000 m, thus rendering the thermal aspect a most important one with rock temperatures on the tunnel trajectory level in excess of 40-50°C. Exemplarily, the temperature evolution forecast for the LTF project is depicted in Fig. 1.

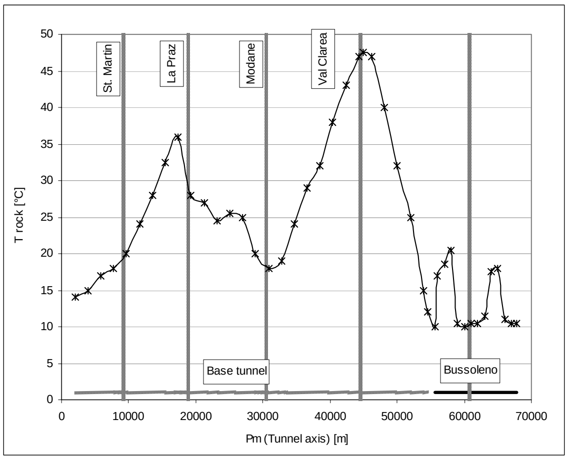

Fig. 1: Exemplary temperature profile, LTF.

REGULATIONS & RECOMMENDATIONS

The present paper is somewhat focused on the European LTF project. Consequently, mainly the relative prescriptions shall be discussed.

France

In France, two recommendations deal with underground construction site ventilation systems, namely the Recommendation R352 of the CNAM [1] and the more recent AFTES Recommendation [2].

Italy

The « Presidential decree » 320 from 1956 is the Italian legal basis. However, this document is not very specific in regard to construction site ventilation and only regulates the fresh air need of a worker, that the air shall remain breathable and as far as possible exempt of pollutants.
Regional public administrations, however, do recommend more specific conditions, such as the “Regione Emilia-Romagna” [4] and particularly in regard to the LTF project the “Regione Piemonte” [5].

Switzerland, CH:
Although Switzerland is not directly involved in the LTF project, the experience collected during the ongoing AlpTransit projects is currently knowledge-transferred in rather large scale. In regard to tunnel construction site ventilation, Switzerland disposes of a specific and detailed regulation [6], which is quoted regularly also in other countries.

Value	France CNAM	France AFTES	CH	I: Emilia-Romagna	I: Piemonte
Fresh air need per CV Diesel	50 l/s	50 l/s	work: 50-74 l/s transport: 25-37 l/s max. without filter	50 l/s	50 l/s
Min. air speed	0.3 m/s	0.5 m/s	0.3 m/s (0.5 m/s if CH_4)	0.2 m/s	0.3 m/s
Max. air speed		1.5 m/s			
Temperature, work site		26°C humid	28°C dry		25°C wet bulb
Recommended type	exhaust	exhaust	circul., blowing	blowing	exhaust

Tab. 1: Comparison of prescriptions.

Tab. 1 compares the cited prescriptions. In terms of fresh air needs, only the Swiss values differ somewhat in function of Diesel engine dust-filter presence and the type of the engine employment, either at the work front or down road in the tunnel. In terms of minimal air speed, the recent French AFTES recommendation is the most restrictive requiring a least 0.5 m/s. It is also the only document, which defines an upper bound for air speed (1.5 m/s). Concerning temperatures the Italian prescription for LTF from Piemonte is the most stringent allowing a highest worksite wet bulb temperature of only 25°C. In regard to the ventilation system type, both French recommendations emphasize the importance of efficient dust and blasting fume capture at its origin and removal to the exterior, implying thus the employment of exhaust ventilation systems.

WORK SITE VENTILATION

Fresh air requirements, example LTF
The vehicles typically in service within a construction site are listed in Tab. 2 both for conventional excavation by blasting as well as for boring-machine tunneling. Based on a fresh air rate of 50 l/s per CV, 48.3 m^3/s are required for blast heading whereas for the mechanized heading 26.6 m^3/s are necessary. As the cross section of the main tubes of the LTF project is approx. 85 m^2, the fresh air requirement for the boring-machine advances must be increased to 42.5 m^3/s to fulfill also the AFTES minimum speed rule of 0.5 m/s.

WORK SITE COOLING

Heat load from the rock mass
The temperature profile along the tunnel axis is depicted in Fig. 1. The heat transfer calculation from the tunnel wall to the air is rather complex, because it depends at each axial location on the excavation time history and the related wall temperature cool down. The influencing parameters are:

- Local convective heat transfer coefficient (function of Reynolds number, wall roughness and tunnel diameter)
- Initial wall temperature (temperature of the rock mass)
- Air temperature in the tunnel
- Tunnel age, function of excavation length and excavation speed.

For the present calculations, the following constant physical properties of the rock are considered:

Thermal capacity:	900 J/(kg K)
Conductivity:	2.3 W/(m K)
Density:	2600 kg/m^3

The radial heat transfer may be resolved numerically or analytically. In the former case, also variable properties in terms of space and temperature may be included.
Additional heat input related to warm water seepage through the rock may be taken into account with an enhancement factor applied to the thermal conductivity.

		Fresh air per kW	4.08 m^3/min		(AFTES 2003)					
Excavation type	Work site	Equipment	N°	Drive	Power [kW]	Load factor	time factor	Fresh air and suction requirements [m^3/s]		
								Diesel	Dust	Max.
Blasting	Mucking	Wheel loader	1	Diesel	235	0.7	100%	11.18		
	Mucking	Crusher	1	Diesel	135	0.7	100%	6.42		
	Shotcrete	Shotcrete pump	1	Diesel	85	0.7	100%	4.04	10	
	Shotcrete	Concrete truck	1	Diesel	80	0.7	100%	3.81		
	Final lining	Concrete truck	1	Diesel	80	0.7	100%	3.81		
	Final lining	Mobile pump	1	Diesel	80	0.7	100%	3.81		
	Finiture	Concrete truck	1	Diesel	80	0.7	100%	3.81		
	Finiture	Mobile pump	1	Diesel	80	0.7	100%	3.81		
	Transport	Truck	2	Diesel	160	0.7	100%	7.61		
								48.3	**10**	**48.3**
Boring machine	Tunnel boring machine	TBM	1	elect.			50%		10	
	Shotcrete	Shotcrete pump	1	elect.			50%		10	
	Shotcrete	Concrete truck	1	Diesel	80	0.7	100%	3.81		
	Final lining	Concrete truck	1	Diesel	80	0.7	100%	3.81		
	Final lining	Mobile pump	1	Diesel	80	0.7	100%	3.81		
	Finiture	Concrete truck	1	Diesel	80	0.7	100%	3.81		
	Finiture	Mobile pump	1	Diesel	80	0.7	100%	3.81		
	Transport	Truck	2	Diesel	160	0.7	100%	7.61		
								26.6	**20**	**26.6**

Tab. 2 : Exemplary fresh air requirements, based on 50 l/s and CV.

Heat dissipated by engine-driven equipment

In case of tunnel boring-machine (TBM) excavation works, the latter represents a major source of heat release. About 60% of the absorbed power (approx. 5 MW for an excavation diameter of 10 m) is used to detach rock chips, which are hereby heated-up to a temperature approx. 40°C above its initial value. The remaining 40% are equipment-related losses, which are directly cooled away. These losses develop within the electric and hydraulic drives or the frequency converters.

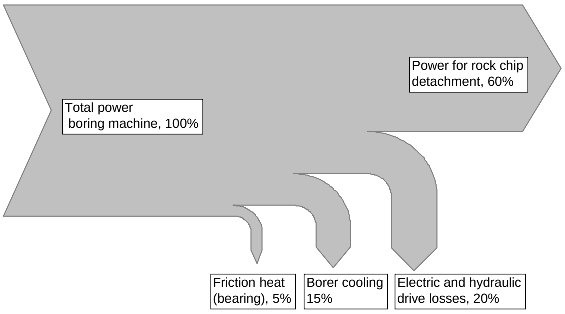

Fig. 2: Typical boring-machine heat balance.

The typical time usage factor of a boring-machine is 30%-50%. The remaining time is required, among others, for its displacement, material supply and maintenance. Taking into account these periods of inactivity, the necessary tunnel air cooling power may be reduced proportionally. The cooling system design basis is thus rather the average power consumed instead of the installed power. This approach is justified by the thermal inertia of the rock, which releases the absorbed heat rather slowly.

The heat dissipated by other equipment is less important. For Diesel engine driven vehicles, the mechanical power values listed in Tab. 2 must be corrected with the engine efficiency of about 30% to obtain the total dissipated heat.

The heat dissipation of the ventilation fans is obtained considering a global fan efficiency of 70%.

Heat of cement setting

Cement setting is an exothermal chemical process, during which the hydration heat is released. It amounts to 380 kJ of heat per kg of cement. In the present calculations, 400 kg of cement are taken into account for each m^3 of concrete.

Heat released during mucking

The muck spoil cools down when transported away by mucking trains or trucks. As a conservative approach, total cool down is assumed here.

Environmental conditions

The external ambient conditions of the air fed into the tunnel work site are usually taken as follows:

• Temperature:	20°C
• Initial humidity:	100%

Evaporative cooling is therefore normally not considered, as it depends heavily on the initial humidity conditions and could yield an under dimensioned cooling system during hot and humid periods.

COOLING CONCEPT FOR LTF

For the LTF project, a modular, flexible and easily extensible remote cooling system has been adopted, which relies on combined chiller and radiator units being distributed in the areas where cooling is required (Fig. 3). This type of equipment is available with cooling capacities of approx. 150 to 400 kW and can be easily accommodated within the working areas to directly cool the tunnel air. The heat is removed from these chillers to a water ring piping, which in turn is re-cooled externally in a cooling tower.

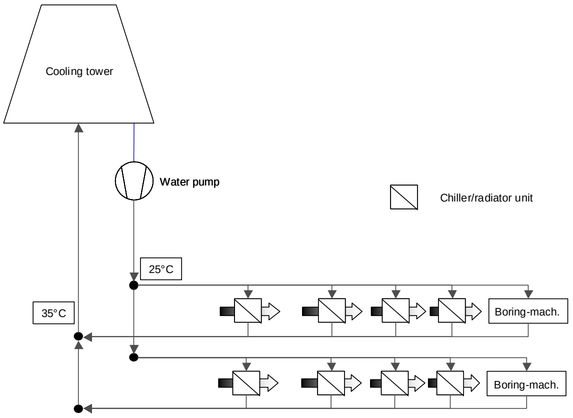

Fig. 3: Cooling concept.

CALCULATION SCHEME

The tunnel ventilation and cooling calculation code uses a one-dimensional model to solve the equations in a discrete manner based on elements of constant length dx. The tunnel is furthermore divided into functional segments according to the local ventilation schemes applied (blowing, exhaust or circulation ventilation).

$$M_i = M_{i-1} + \left(M_i^{in} - M_i^{out} + M_i^{leakage}\right)$$

$$u_i = \frac{M_i}{A_i \rho_i}$$

$$\alpha_i = \frac{Nu_i^D \left(Re_i^D, Pr, roughness\right) \cdot k}{D_i^{hyd}}$$

$$Q_i^{wall} = S_i \cdot \alpha_i \left(T_i^{wall} - T_i\right)$$

$$T_i = T_{i-1} + \frac{Q_i^{wall} + Q_i^{duct} N_{duct} + \dfrac{P_i^{Diesel} g_i}{\eta_{Diesel}} + Q_i^{TBM} + Q_i^{concrete} - Q_i^{cool}}{M_i \cdot C_p}$$

$$T_i = \frac{M_i \cdot c_p \cdot T_i + M_i^{leakage} c_p \cdot T_i^{duct}}{M_i \cdot c_p + M_i^{leakage} c_p}$$

$$p_i = p_{i-1} + \frac{\rho_i}{2} u_i \left|u_i\right| \cdot \left[\lambda_{\left(Re_i^D, roughess\right)} \frac{dx_i}{D_i^{hyd}} + \sum \zeta_i\right]$$

Eq. 1: Tunnel computation

The computation is then carried out sequentially for each segment resolving first the flow in the tunnel itself (Eq. 1) and thereafter in the duct for blowing ventilation (Eq. 2) or vice-versa for exhaust ventilation, respectively.

$$M_i^{duct} = M_{i-1}^{duct} - \frac{M_{i-1}^{leakage}}{N_{duct}}$$

$$u_i^{duct} = \frac{V_i^{duct}}{A_i^{duct} \rho_i^{duct}}$$

$$Q_i^{duct} = S_i^{duct} \cdot U_i^{duct} \left(T_i^{duct} - T_i\right)$$

$$T_i^{duct} = T_{i-1}^{duct} - \frac{Q_i^{duct} - Q_i^{fan} + Q_i^{duct,cool}}{M_i^{duct} \cdot C_p}$$

$$p_i^{duct} = p_{i-1}^{duct} - \frac{\rho_i^{duct}}{2} u_i^{duct} \left|u_i^{duct}\right| \left[\lambda_{duct} \frac{dx_i}{D_i^{duct}} + \sum \zeta_i^{duct}\right]$$

$$dp = p_i^{duct} - p_i$$

$$u_{leakage} = \sqrt{\frac{dp}{\frac{\rho_i^{duct}}{2}\left(1 + \zeta_{Leakage}\right)}}$$

$$M_i^{leakage} = N_{duct} \cdot u_{leakage} \cdot S_i^{duct} \cdot S^{leakage} \cdot \rho_i^{duct}$$

Eq. 2: Duct computation

The transient heat transfer from the wall to the air is either resolved numerically with a radial heat conduction explicit scheme and a convective boundary condition:

$$\frac{\partial T}{\partial t} = \frac{\Lambda}{r} \frac{\partial}{\partial r}\left(r \frac{\partial T}{\partial r}\right)$$

$$-\lambda \left.\frac{\partial T}{\partial t}\right|_{r=0} = \alpha\left(T_{air} - T(0,t)\right)$$

for $j = 1$:

$$T_j^{p+1} = 2 \cdot Fo\left(T_{j+1}^p + Bi \cdot T_{air}\right) + \left(1 - 2 \cdot Fo - 2 \cdot Bi \cdot Fo\right) \cdot T_j^p$$

for $j > 1$:

$$T_j^{p+1} = \Lambda dt\left(\frac{1}{2R_j dR}\left(T_{j+1}^p - T_{j-1}^p\right) + \frac{1}{dR^2}\left(T_{j+1}^p + T_{j-1}^p - 2T_j^p\right)\right) + T_j^p$$

Eq. 3: Radial transient heat conduction, numerical solution.

or with a semi-infinte plane wall analytical solution:

$$\frac{T_{wall}(t) - T_i}{T_{air} - T_i} = -\exp\left(\omega^2\right) erfc(\omega)$$

$$\omega = \frac{\alpha\sqrt{\Lambda t}}{\lambda}$$

Eq. 4: Transient heat conduction, analytical solution.

The latter accelerates the calculation considerably, but is valid only for constant rock properties and sufficiently large tunnel diameters to approximate the actually curved surface with a plane wall. Furthermore, a constant air temperature must be also assumed, whereas the numerical solution may account for time-dependent tunnel temperature profiles.

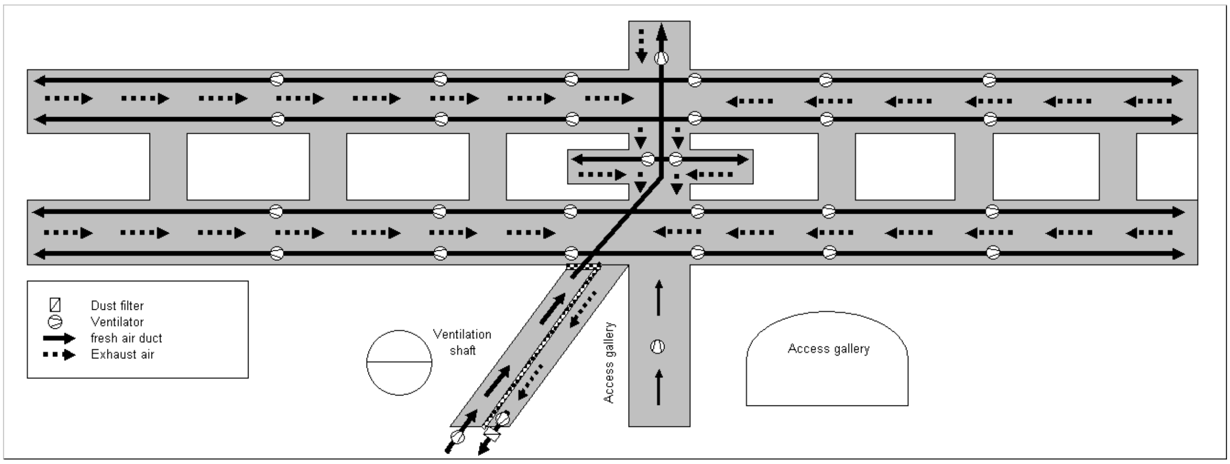

Fig. 4: Modane intermediate site with forced ventilation system.

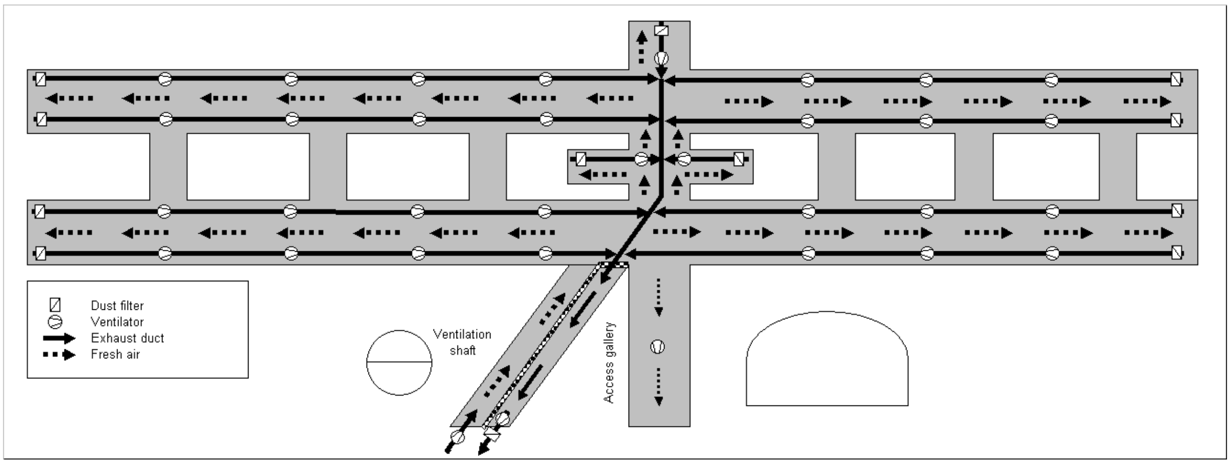

Fig. 5: Modane intermediate site with exhaust ventilation system.

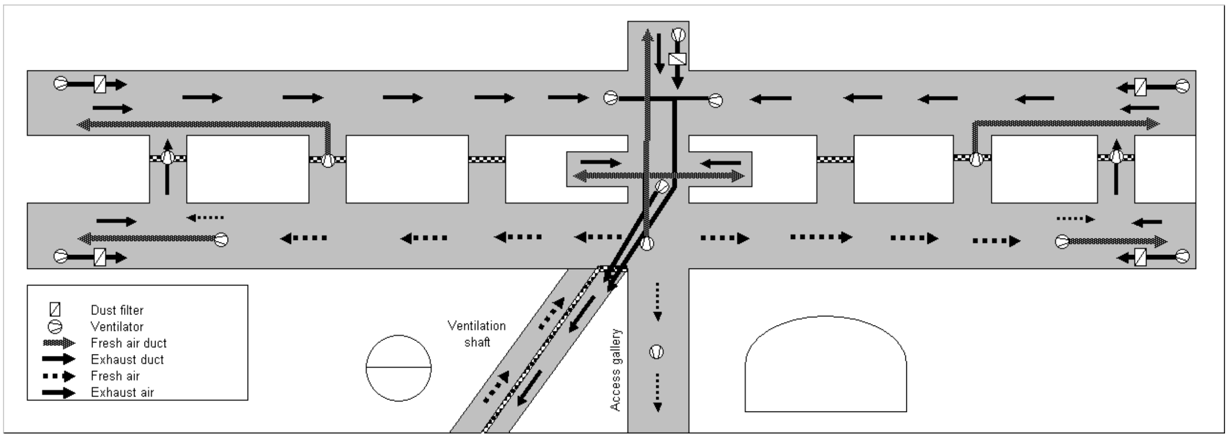

Fig. 6: Modane intermediate site with circulation ventilation system.

Duct characteristics

The ventilation duct leakages and friction losses are calculated according to the values given in [2] and [6] for various duct types.

Duct type	Friction coefficient, λ	Active leakage surface, f*
Flexible forced, class S	0.015	5 mm^2/m^2
Flexible forced, class A	0.018	10 mm^2/m^2
Flexible forced, class B	0.024	20 mm^2/m^2
Flexible exhaust, reinforced with helical-wound spring steel	0.025	5-20 mm^2/m^2
Sheet metal duct	0.010	2 mm^2/m^2

FORCED VENTILATION EXAMPLE

Forced ventilation schemes are generally not considered for the LTF project because of the specific French guidelines [1] and [2], which strongly recommend dust and blasting fume capture at its origin and removal to the exterior.

The following example of blowing ventilation is nevertheless based on a LTF excavation geometry, namely the eastern advancements of the Modane intermediate construction site (Fig. 4). The main characteristics are:

o Max. excavation length	9.8 km
o Excavation type	TBM
o Advancement	4500 m/a
o Excavated diameter	10.4 m
o Excavated section	85 m^2
o Diameter after shotcrete lining	9.8 m
o Section after shotcrete lining	75 m^2
o Final diameter	8.4 m
o Final section	51 m^2
o Fresh air requirement (Tab. 2)	27 m^2/s
o Air required for 0.5 m/s	42.5 m^3/s
o Duct diameters	2 m
o No. of ducts	2
o Max. duct pressure	2500 Pa

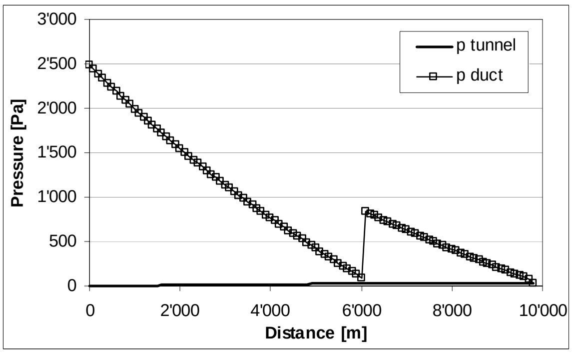

Fig. 7: Modane eastern bores with blowing ventilation, pressure evolution.

The results presents hereafter have been obtained for an S-class duct (new material, very carefully mounted).

As the maximum duct pressure considered is limited to 2500 Pa, the duct must be split into two segments with a booster ventilator station after about 6000 m (Fig. 7).

To avoid the inflow of polluted air returning through the tunnel, the fresh air flowrate exiting the first segment must exceed the flowrate of the booster ventilator by 10-20% [2], [6], Fig. 8. This flow interaction is fully taken into account both aerodynamically as well as in terms of mixing temperature. The same is true for the continuous leakage flowrate of the duct. In addition to this mixing temperature effect, the conductive/convective heat transfer from the tunnel into the duct is also accounted for.

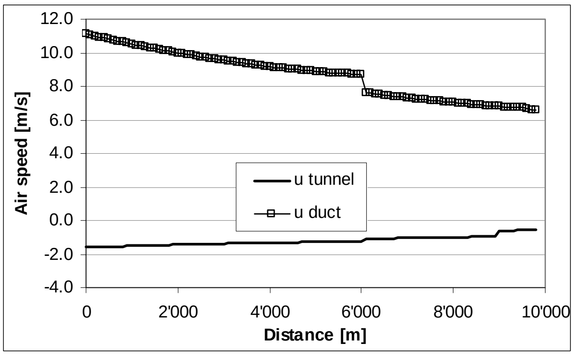

Fig. 8: Modane eastern bores with blowing ventilation, air speed.

The temperature evolution of the tunnel and duct air and the tunnel wall for a rather continuous rise of the rock temperature from the intermediate site is depicted in Fig. 9. The duct air taken outside rises due to heat exchange along the first duct segment. At the booster station the duct temperature jumps by some degrees due to the fan heat input and then decreases slightly further inwards due to the cooler surrounding tunnel air, before being released through a chiller unit at the excavation site.

The back-flowing tunnel air is cooled in the work areas at and downstream of the excavation site and exhibits therefore a saw tooth profile due to the discrete chiller locations. At the booster station, a sudden temperature reduction of the tunnel air takes place due to mixing with the surplus fresh air from the first duct segment.

The wall temperature dips rapidly from its maximum value at the excavation site because of the transient cooling process of the rock mass and thus the growing thermal boundary layer in the solid.

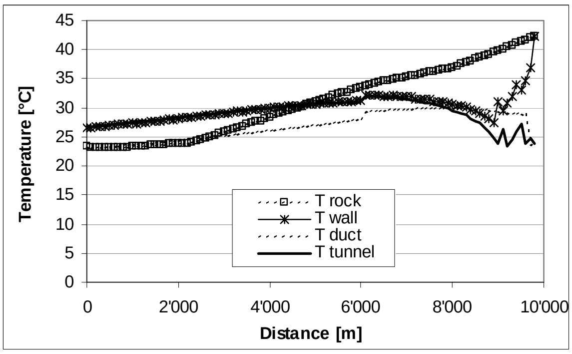

Fig. 9: Modane eastern bores with blowing ventilation, temperatures.

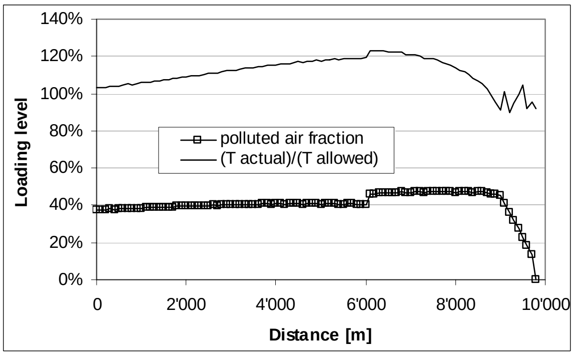

Fig. 10: Modane eastern bores with blowing ventilation, pollution and thermal loading levels with S-type ducts.

Fig. 10 depicts the pollution and thermal loading levels within the tunnel, with the pollution level referring to the ratio of fresh air in respect to the consumed air from Diesel exhaust gases. At the excavation site, fresh air arrives, which is quickly loaded by the local machinery and vehicles in the backward working areas. Downstream of the working areas, only weak linear pollution sources representing the transportation trucks add additional loading, which is however overbalanced by the continuous fresh air leakage of the ducts.

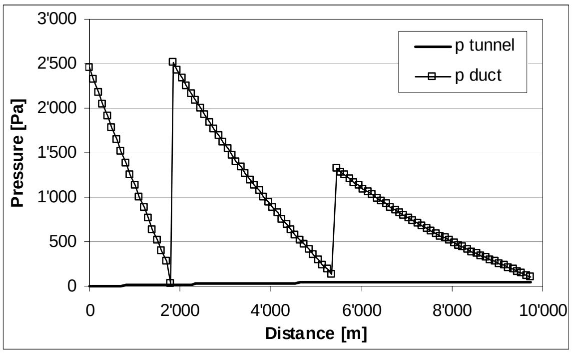

Fig. 11: Modane eastern bores with blowing ventilation, pressure evolution with A-type ducts.

Employing standard quality A-type ducts instead of the high quality S-type ones changes the equipment requirements largely. In order to respect the minimum air velocity of 0.5 m/s (Fig. 12), a 60% higher initial flowrate is required because of the increased leakage rates and higher friction, which in turn renders 3 instead of 2 booster stations necessary, Fig. 11.

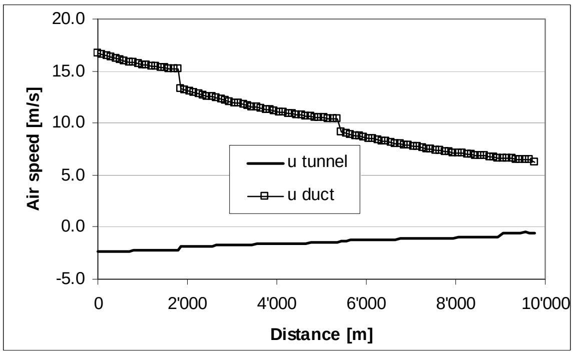

Fig. 12: Modane eastern bores with blowing ventilation, air speed with A-type ducts.

EXHAUST VENTILATION EXAMPLE

The schematic of an exhaust ventilation system for the excavation sites departing from the Modane intermediate construction site is depicted in Fig. 5. This approach is fully compatible with the French recommendations and does not restrict the infrastructure, as the crossway may remain open.

To ensure that the captured dust loaded air is safely extracted without any leakage, the exhaust dust must be operated at negative pressure. Typical ventilation spiral steel sheet ducts support at the most about 750 Pa depression, requiring thus a certain number of booster stations.

The main characteristics of the ducts are now:

o Duct diameter	2 m
o No. of ducts	2
o Max. duct pressure	-750 Pa

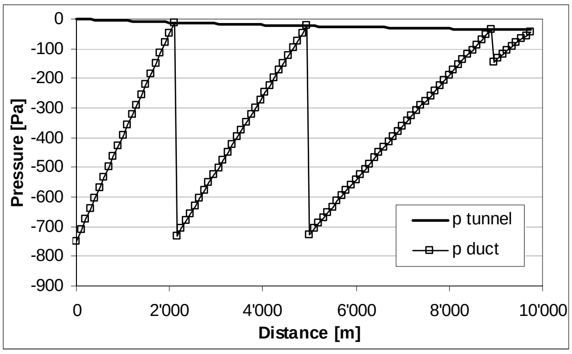

Fig. 13: Modane eastern bores with exhaust ventilation, pressure evolution.

The results for the present geometry show, that 4 booster stations are required, Fig. 13.

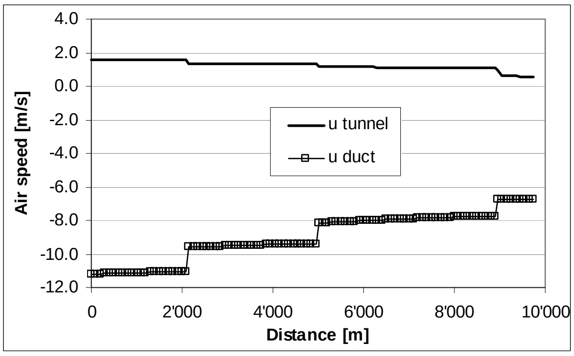

Fig. 14: Modane eastern bores with exhaust ventilation, air speed.

As the fresh air is provided through the plain tunnel section, the air temperature heats gradually up as the wall temperature rises. At the work sites, suitably installed chillers reduce the temperature to the required level. At the excavation front, the air is sucked into the exhaust ducts and carried away (Fig. 15).

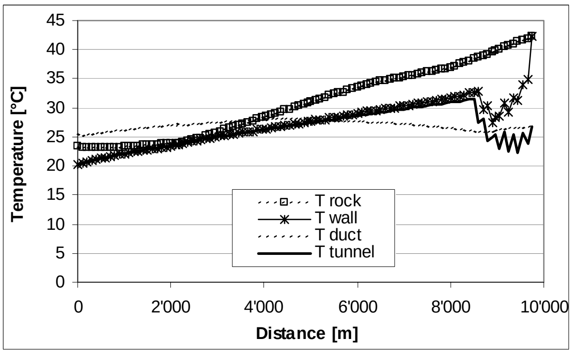

Fig. 15: Modane eastern bores with exhaust ventilation, temperatures.

The pollution level of the inflowing air increases first gradually due to the transportation truck line sources. A steeper rise occurs at the work sites backward and at the excavation front. As the total air flowrate is dictated by the minimum air speed of 0.5 m/s and not the fresh air requirements of the Diesel engines, the air loading does not exceed 60%.

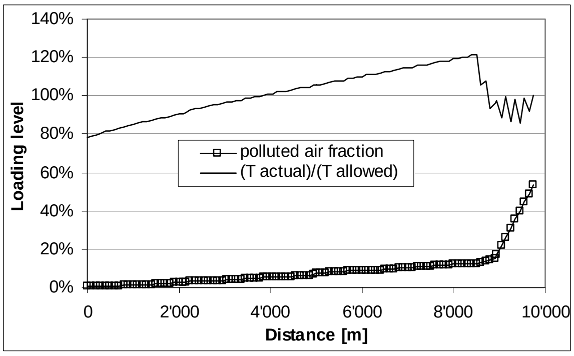

Fig. 16: Modane eastern bores with exhaust ventilation, pollution and thermal loading levels.

CIRCULATION VENTILATION EXAMPLE

The layout of the Modane construction site with a circulation ventilation system is depicted in Fig. 6. This system has a strong impact on the construction infrastructure and logistics, as it requires an aerodynamic separation of the two parallel tunnel bores and thus closed crossways.

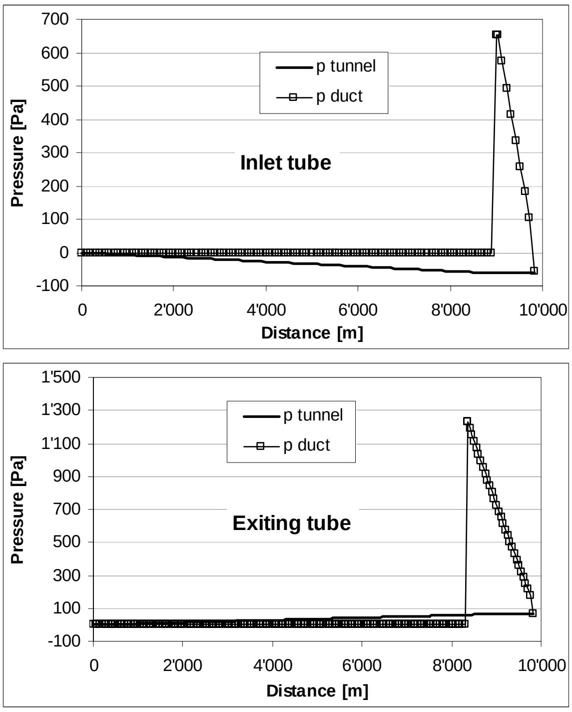

Fig. 17: Modane eastern bores with circulation ventilation, pressure evolution.

In fact, the first tube provides fresh air for both excavation sites. In some distance from the front, fresh air is drawn into the second tube and delivered to its extremity through a flexible ventilation duct. For the first tube, a duct is equally employed to bring the fresh air to the front. The consumed air from the first tube then flows back and is transferred into the second tube by means of a ventilator installed in a crossway barrier. The combined loaded air streams are returned through the plain section of the exiting tube.

The typical evolutions of the main quantities are illustrated in the following figures. The inlet tube is operated with negative pressure, whereas the exiting tube is slightly pressurized, Fig. 17.

The pollution level increases gradually in the inlet tube due to the transportation truck line sources (Fig. 18). Close the excavation site, the back-flowing air is loaded by the local Diesel machinery. The excavation site of the second tube receives rather clean air, which has been extracted at a low pollution level from the first tube.

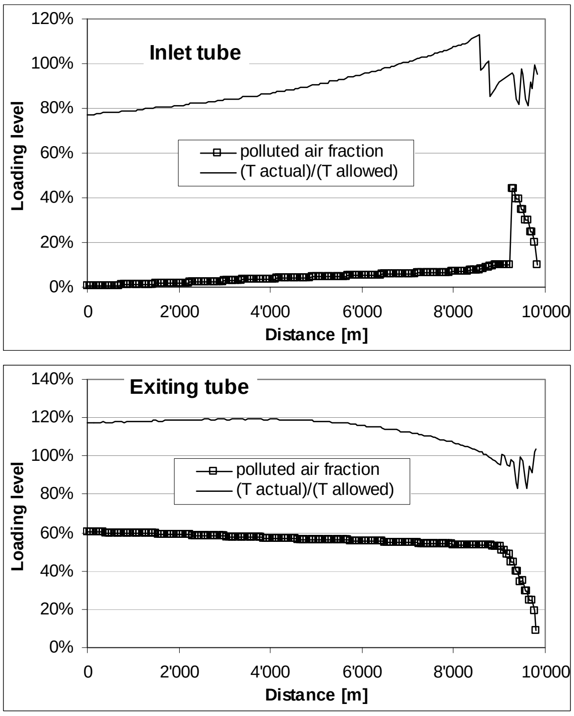

Fig. 18: Modane eastern bores with circulation ventilation, pollution and thermal loading levels.

CONCLUSIONS

The previously described 3 ventilation schemes are compared below in terms of air flow requirements and power consumption for the two eastern tunnel bores excavated from the Modane construction site. The factor 2 in the table refers to the two bores.

	Forced S-type	Forced A-type	Exhaust	Circulation
Initial air flow	2x70 m^3/s =140 m^3/s	2x105 m^3/s =210 m^3/s	2x70 m^3/s =140 m3/s	90 m^3/s
Ventilators/ boosters	2	3	4	3
Ventilation power	2x305 kW =610 kW	2x780 kW =1560 kW	2x200 kW =400 kW	115 kW

1. Circulation ventilation is aerodynamically the best choice, as flow leakage is no issue and friction is low because the plain sections of the tubes are used. Also, the ventilation equipment costs are low. On the other hand, however, the logistics and infrastructure are handicapped, as the crossways must remain closed. Furthermore, the French requirements of dust and blasting fume capture at its origin and removal to the exterior are not fulfilled and would require separate extraction ducting.
2. Forced ventilation schemes are rather cheap, as standard flexible ducting can be used. This equipment is on the other hand not particularly tight, resulting thus in high power requirements due to the rather important leakage flows. As already pointed out, these schemes are not recommended in France without separate extraction ducting.
3. Exhaust ventilation is expensive in terms of capital costs, as several booster stations are required and spiral steel sheet pipes must be installed. Power consumption on the other hand is moderate and the scheme is compatible with French requirements, which are applicable to all LTF construction sites, including the Italian ones. It is thus this scheme, which has been generally adopted for the LTF construction site ventilation systems.

REFERENCES

[1] Caisse nationale de l'assurance maladie des travailleurs salaries, « Mise en œuvre de dispositifs de ventilation mécanique lors des travaux de creusement en souterrains de galeries, de puits, ou de grandes excavations », Recommandation R352 adoptée le 27 juin 1990

[2] AFTES (France), « Recommandations Relatives à la Ventilation des Ouvrages Souterrains en Cours de Construction », p. 76-106, Tunnels et ouvrages souterrains – N° 176, mars/avril 2003

[3] Decreto del Presidente della Repubblica (DPR) 20 marzo 1956, n. 320, « Norme per la prevenzione degli infortuni e L'igiene del lavoro in sotterraneo »

[4] Dossier 28, Regione Emilia-Romagna /CDS, Aziende USL Città di Bologna e Ravenna, «Gli scavi in sotterraneo – Analisi dei rischi e normativa in materia di sicurezza», Novembre 1996

[5] Ministero del Lavoro e delle Politiche Sociali, Direzione Regionale del Lavoro del Piemonte, « Indirizzi operativi comuni per la costruzione in sicurezza del megatunnel sulla linea ferroviaria Torino-Lione », Giunio 2005

[6] SIA 196, « Ventilation des chantiers souterrains», 1998