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**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>cross section</td>
<td>m²</td>
</tr>
<tr>
<td>Bi</td>
<td>Biot number</td>
<td>-</td>
</tr>
<tr>
<td>C₀</td>
<td>thermal capacity</td>
<td>J/(kg K)</td>
</tr>
<tr>
<td>D</td>
<td>diameter</td>
<td>m</td>
</tr>
<tr>
<td>fₕ</td>
<td>active leakage area</td>
<td>m²/m²</td>
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<td>Fourrier number</td>
<td>-</td>
</tr>
<tr>
<td>g</td>
<td>usage factor</td>
<td>-</td>
</tr>
<tr>
<td>k</td>
<td>thermal conductivity</td>
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<tr>
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<td>mass flow</td>
<td>kg/s</td>
</tr>
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<td>-</td>
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<td>p</td>
<td>total pressure</td>
<td>Pa</td>
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<tr>
<td>P</td>
<td>power Diesel engines</td>
<td>kW</td>
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<tr>
<td>Pr</td>
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<td>Q</td>
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<td>S</td>
<td>surface</td>
<td>m²</td>
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<td>T</td>
<td>temperature</td>
<td>°C</td>
</tr>
<tr>
<td>u</td>
<td>speed</td>
<td>m/s</td>
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<tr>
<td>U</td>
<td>total thermal resistance</td>
<td>W/m²·K</td>
</tr>
<tr>
<td>V</td>
<td>volume flow</td>
<td>m³/s</td>
</tr>
<tr>
<td>x</td>
<td>distance</td>
<td>m</td>
</tr>
<tr>
<td>α</td>
<td>convection coefficient</td>
<td>W/(m²·K)</td>
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<tr>
<td>Λ</td>
<td>thermal diffusivity</td>
<td>m²/s</td>
</tr>
<tr>
<td>η</td>
<td>efficiency</td>
<td>-</td>
</tr>
<tr>
<td>λ</td>
<td>friction coefficient</td>
<td>-</td>
</tr>
<tr>
<td>ρ</td>
<td>density</td>
<td>kg/m³</td>
</tr>
<tr>
<td>ζ</td>
<td>pressure loss coefficient</td>
<td>-</td>
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</table>

**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 workforce 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.

**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].

![Exemplary temperature profile, LTF.](image-url)
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.

<table>
<thead>
<tr>
<th>Value</th>
<th>France CNAM</th>
<th>France AFTES</th>
<th>CH</th>
<th>Emilia-Romagna</th>
<th>Piemonte</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh air need per CV Diesel</td>
<td>50 l/s</td>
<td>50 l/s</td>
<td>work: 50-74 l/s transport: 25-37 l/s max. without filter</td>
<td>50 l/s</td>
<td>50 l/s</td>
</tr>
<tr>
<td>Min. air speed</td>
<td>0.3 m/s</td>
<td>0.5 m/s</td>
<td>0.3 m/s (0.5 m/s if CH₄)</td>
<td>0.2 m/s</td>
<td>0.3 m/s</td>
</tr>
<tr>
<td>Max. air speed</td>
<td>1.5 m/s</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature, work site</td>
<td>26°C humid</td>
<td>28°C dry</td>
<td>25°C wet bulb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recommended type</td>
<td>exhaust</td>
<td>exhaust</td>
<td>circul., blowing</td>
<td>exhaust</td>
<td></td>
</tr>
</tbody>
</table>

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 m³/s are required for blast heading whereas for the mechanized heading 26.6 m³/s are necessary. As the cross section of the main tubes of the LTF project is approx. 85 m², the fresh air requirement for the boring-machine advances must be increased to 42.5 m³/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/m³

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.
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.

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%.

Cement setting is an exothermic 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.

**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).

\[ M_i = M_{in} + (M_{in} - M_{out} + M_{leakage}) \]

\[ u_i = \frac{M_i}{A_{bi}} \]

\[ \alpha_i = \frac{N_{bi}(P_{in} - P_{rough})}{D_{bi}} \]

\[ Q_{wall} = S_i \cdot \alpha_i \cdot (T_{wall} - T_i) \]

\[ T_i = T_{t,1} + \frac{Q_{wall} + Q_{duct} + \frac{P_{in} + P_{t}}{D_{bi}} + Q_{t} - Q_{cool}}{M_i \cdot C_p} \]

\[ p_i = p_{in} + \frac{p_{in} + p_{t}}{2} \]

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.

\[ M_{leakage} = \sum_{i} u_{leakage} \cdot Q_{leakage} \cdot T_{leakage} \]

\[ u_{leakage} = \frac{u}{A_{leakage}} \]

\[ Q_{leakage} = \sum_{i} \left( \frac{Q_{in} - Q_{out} - Q_{cool}}{M_{leakage}} \right) \]

\[ T_{leakage} = T_{leakage} \]

\[ \rho_{leakage} = \sum_{i} \left( \frac{\rho_{leakage}}{M_{leakage}} \right) \]

**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:

\[ \frac{dT}{dt} = \frac{\alpha_i}{A_{bi}} \left( T_{wall} - T_i \right) \]

\[ \lambda \cdot \frac{dT}{dt} \]

\[ \frac{dT}{dt} = \alpha_i (T_{wall} - T_i) \]

for \( j = 1 \):

\[ T_{j+1} = T_{j} + \rho_{j} \cdot \frac{dT}{dt} \]

for \( j > 1 \):

\[ T_{j+1} = A \cdot \frac{1}{2 \pi R} \left( T_{j} - T_{j+1} \right) + \frac{1}{2 \pi R^2} \cdot \frac{dT}{dt} \]

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

or with a semi-infinite plane wall analytical solution:

\[ T_{wall}(t) = T_{wall} - \frac{1}{\pi} \cdot \frac{1}{\lambda} \int_{0}^{t} \lambda \cdot \frac{dT}{dt} \cdot \exp(-\frac{t-t_i}{\lambda}) \cdot \exp(-\frac{t-t_i}{\lambda}) \]

**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.

<table>
<thead>
<tr>
<th>Duct type</th>
<th>Friction coefficient, ( \lambda )</th>
<th>Active leakage surface, ( f^* )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible forced, class S</td>
<td>0.015</td>
<td>5 mm(^2)/m(^2)</td>
</tr>
<tr>
<td>Flexible forced, class A</td>
<td>0.018</td>
<td>10 mm(^2)/m(^2)</td>
</tr>
<tr>
<td>Flexible forced, class B</td>
<td>0.024</td>
<td>20 mm(^2)/m(^2)</td>
</tr>
<tr>
<td>Flexible exhaust, reinforced with helical-wound spring steel</td>
<td>0.025</td>
<td>5-20 mm(^2)/m(^2)</td>
</tr>
<tr>
<td>Sheet metal duct</td>
<td>0.010</td>
<td>2 mm(^2)/m(^2)</td>
</tr>
</tbody>
</table>

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:

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

The results presented 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.

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

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

Fig. 9: Modane eastern bores with blowing ventilation, temperature evolution.
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:

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

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.

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

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%.

In fact, the first tube provides fresh air for both excavations. 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.

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.

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.

<table>
<thead>
<tr>
<th></th>
<th>Forced A-type</th>
<th>Exhaust Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial air flow</td>
<td>2x70 m³/s</td>
<td>2x105 m³/s</td>
</tr>
<tr>
<td>Ventilators/boosters</td>
<td>&gt;210 m³/s</td>
<td>2x70 m³/s &gt;140 m³/s</td>
</tr>
<tr>
<td>Ventilation power</td>
<td>2x305 kWe</td>
<td>2x780 kW &gt;1560 kW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2x290 kW &gt;400 kW</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90 m³/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td>115 kW</td>
</tr>
</tbody>
</table>

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


