Environmentally Friendly Ventilation of Complex Underground Infrastructures

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ABSTRACT: Ventilation is a primary requirement for all kinds of complex underground facilities, both in normal operating conditions and in case of fire. Experience shows that the environmental footprint of complex ventilation systems can be very large. Different ventilation concepts used for underground facilities can have widely different energy consumptions. The present paper focuses on the importance of reducing the environmental impact of such facilities by means of energy-efficient ventilation systems, for example by using natural ventilation in an extensive manner.

KEYWORDS: Ventilation, Underground space, Energy efficiency, Natural ventilation

1. INTRODUCTION AND OBJECTIVES

The trend towards more extensive use of underground space is unmistakable as surface space in some cities becomes scarce and costly. Complex underground systems such as research and production facilities or nuclear waste storage facilities pose a number of very specific challenges in terms of safety and air quality during normal operation and in case of fire. Some of them are largely common to conventional traffic infrastructures or mines, but other issues are very specific and require dedicated approaches.

Ventilation is invariably one of the major energy consumers in underground facilities. This is particularly so in large underground infrastructures, requiring powerful ventilation systems. Moreover, the ventilation tends to be active virtually permanently during the operating hours of the facilities. This represents an increasing concern and reductions of energy consumption through ventilation is one of the keys for improving the environmental sustainability of such facilities.

This paper focuses on energy optimization of ventilation systems in large underground infrastructures.

2. COMPLEX UNDERGROUND INFRASTRUCTURES

The spectrum of current and emerging uses of underground spaces is wide and includes storage, industrial facilities, research centers, sports and leisure centers, and churches such as the beautiful Rock Church in Helsinki. Admiraal and Cornaro (2018) provided a broad review on the concept of underground space development for investigating the issues associated with the sustainable development of urban underground space.

Figure 1 Data centers are a typical example of "power-hungry" underground systems with very high requirements on ventilation and cooling

Recent developments were reviewed by Bettelini et al. (2020). Some cities, such as Helsinki, already have a wide spectrum of underground facilities (Vähäaho, 2014), including parking, sport facilities, oil and coal storages, etc. Singapore is pursuing an aggressive strategy of developing underground space and set up in 2007 an Underground Master Plan Task Force. This strategy is confirmed by the new Master Plan (URA, 2019).

Since the early 2010s, Hong Kong's Government launched a number of strategic studies and pilot projects for exploring the systematic utilization of rock caverns and underground space. The Cavern Master Plan was developed as a tool providing a broad strategic planning framework to guide and facilitate territory-wide cavern development in Hong Kong. This foresees moving major public facilities into large-span caverns. An impressive example is the Sha Tin Sewage Treatment Plant, which will be moved into a large cavern system and will release 28 ha of land (Figure 2). Another important effort are the feasibility / pilot studies for moving additional services into caverns, such as labs, data centers and a columbarium.

Figure 2 Relocation of Sha Tin Sewage Treatment Works to caverns (Hong Kong)

The availability and applicability of regulations and best practices for complex underground infrastructures are generally very limited. There are sometimes attempts at applying national building codes to "building-like" underground facilities. This should generally be avoided as the requirements and approaches to underground safety are radically different from those of conventional buildings. This was recognized early in Hong Kong, as stated in the introduction to the 1994 Guide to Fire Safety Design for Caverns: "Occupants in underground caverns are subject to different life risks from those in buildings erected above ground, e.g., easy accumulation of smoke and heat, longer traveling distance in escape routes, and lack of external communication" (BAFSD, 1994).

NFPA 520 on subterranean spaces (NFPA, 2016) specifically addresses "the safeguarding of life and property against fire, explosion, and related hazards associated with developed subterranean spaces" and is one of the few regulations developed specifically for underground facilities.

There is currently no regulation worldwide providing guidance for the ventilation of complex underground facilities.

3. ENERGY EFFICIENT VENTILATION

Compared to traffic infrastructures (see e.g. Bettelini, 2020), underground space is characterized by a very large variability in structure, use, and requirements. This results in a wide spectrum of ventilation principles and systems, which represents a major difference compared to traffic infrastructures. A further difference is related to operational conditions. Traffic infrastructures are frequently ventilated only in case of emergency, notably fire. In normal operating conditions, rail tunnels are mostly naturally ventilated. Also in the case of road tunnels, the use of ventilation in normal operating conditions is increasingly limited to transverse ventilations installed in very long road tunnel. The trend is accelerated by new clean vehicle concepts. Metro stations partly represent an exception since a comfort ventilation for the stations can be required. Generally speaking, energy efficiency is frequently a minor concern in underground traffic infrastructures and safety requirements in case of fire pose the most relevant requirements.

Ventilation and HVAC systems for complex underground infrastructures, particularly in case of large occupancy and mixed usages, tend to run permanently. Energy consumption can be very large, and this represents a significant environmental impact as well as an economic burden for these infrastructures. It is therefore essential fostering energy efficiency for such systems. This directly enhances their environmental sustainability, in line with the 1992 United Nations Framework Convention on Climate Change (Rio, 1992) and the subsequent Kyoto (1997) and Paris (2016) agreements.

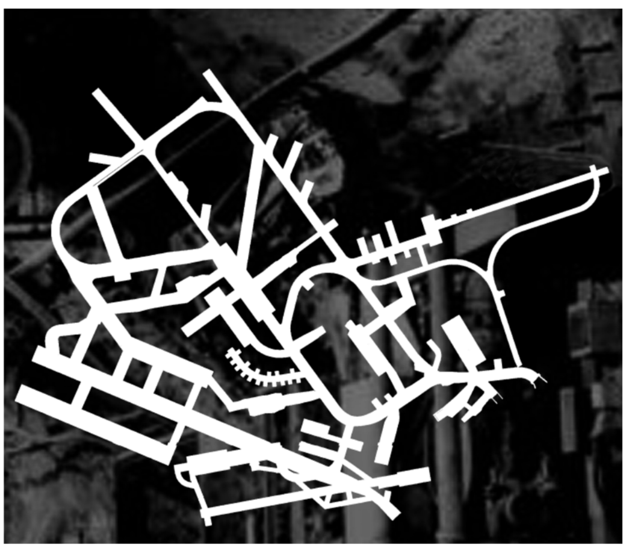

Figure 3 Layout of the Hagerbach Test Gallery

4. ON THE ROLE OF NATURAL VENTILATION

“Traditional” ventilation systems for “conventional” underground facilities, such as mines, are generally based on forced ventilation. Such systems are based on a forced air extraction or injection and a well-defined distribution of air through the underground facility, supported by doors and booster fans. An example is presented in Figure 4.

Forced ventilations generally require a permanent operation of the system while the facility is operated. The ventilation direction is generally defined and does not account for thermal effects, which could at times support or act against the selected ventilation direction. This generally results in high energy consumption and unnecessarily high environmental impact. On the positive side, the operation of such systems is very simple, and a consistent level of air quality can be achieved at any time.

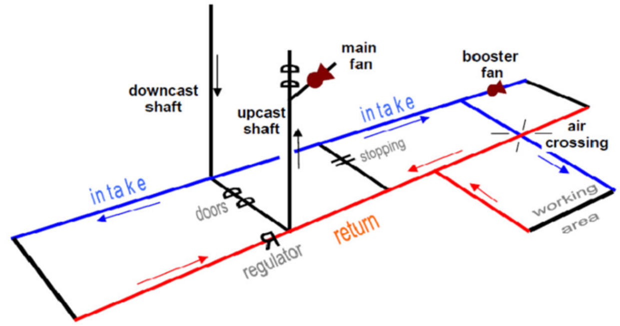

Figure 4 Schematic representation of the Okaba Underground Coal Mine (Nigeria) ventilation system (Akande and Moshood, 2013)

Natural ventilation is driven by natural temperature differences between the inside of a facility and the environment. As a first approximation, the velocity generated by a natural temperature difference can be loosely expressed as follows

$$v \sim \sqrt{\frac{2}{\varsigma} \cdot \frac{\Delta\rho}{\rho} \cdot g \cdot \Delta h} \sim \sqrt{\frac{2}{\varsigma} \cdot \frac{\Delta T}{T} \cdot g \cdot \Delta h}$$

with

ρ	air density
$\Delta\rho$	density difference
T	air temperature
ΔT	temperature difference
Δh	elevation difference
g	gravitational acceleration
ς	global system drag coefficient

Thus, natural ventilation is driven by the interaction between natural temperature differences ΔT between the interior of the system and its environment and the relevant vertical dimension Δh. Some numerical values are illustrated in Figure 5 ($\varsigma = 5$).

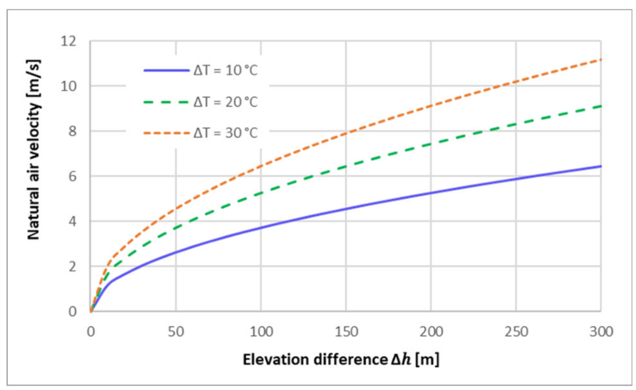

Figure 5 Natural air velocity

The power of such systems is well known from large road and rail tunnels with significant coverage. In the Gotthard Road tunnel (Switzerland, Figure 6), the internal temperature permanently exceeds 30°C. With an external temperature frequently close to freezing and the up to 543 m high shafts, a powerful natural airflow is observed. This natural ventilation significantly reduces the global operating costs of the tunnel.

The multipurpose Hagerbach Test Gallery in Switzerland, with a total length of over 5 km, is a successful example of a very large underground facility with very heterogeneous usages, which is predominantly naturally ventilated (Figure 3).

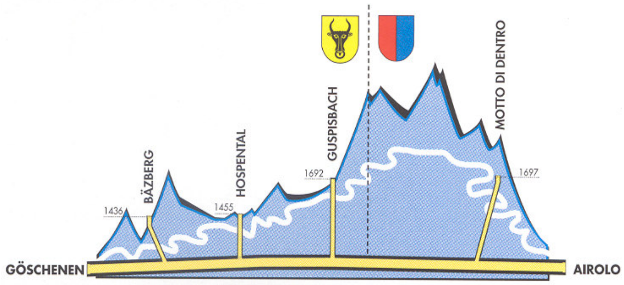

Figure 6 Schematic representation of the 17 km Gotthard Road tunnel with 4 high shafts (Bettelini, 2004)

Many facilities have a significant vertical development, which represents and ideal prerequisite for an extensive use of natural ventilation (Figure 7). It is not surprising, that many such systems exhibit a good level of natural ventilation.

Natural ventilation is not always sufficiently reliable and must be supported in an appropriate manner. Because of the seasonal and daily variations of the external air temperatures, flow reversal between the cold and hot season is quite common. Similarly, different flow patterns are observed along the daily cycle in the morning and in the afternoon (Figure 11). High energy efficiency is achieved if the resulting "stack effect" is properly supported and used to the maximum possible extent.

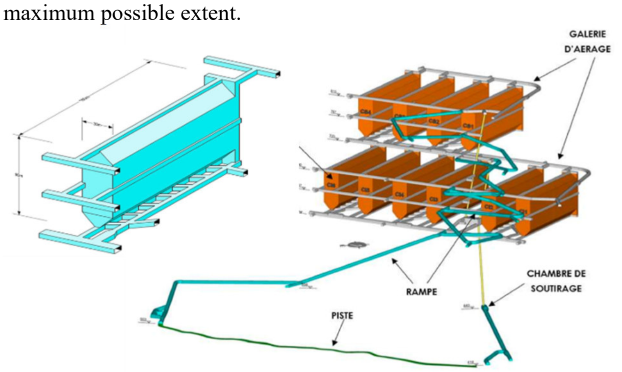

Figure 7 New underground extension of Carrières d'Arvel (Switzerland)

5. ENERGY-EFFICENT VENTILATION

Purely natural ventilation does not require external power and obviously represents the most efficient ventilation system. As discussed above, this provides only in particular cases stable and reliable fresh-air supply to the whole facility. Natural-ventilation patterns are generally well defined in summer and in winter. They are less clearly defined in the intermediate seasons, where the external temperature can fluctuate around the value of the internal temperature, which tends to be quite stable. This leads to transient situations with insufficiently well-defined flow patterns. This can result, depending on the activities carried out in the facility, in pollution build-up, discomfort and complaints.

Principle and layout of ventilation concepts based on natural ventilation depend on the typical internal and external temperature. In case of large coverage, as in the Gotthard Road tunnel, the internal temperature significantly exceeds the external temperature and there is a unique preferred ventilation direction. For facilities built close to the surface, the internal temperature is generally fairly constant and the daily and yearly cycles result in higher or lower external temperatures. Under such conditions, the ventilation system needs to be reversible, as illustrated in the following chapter on the example of the Schollberg underground quarry.

Reversible jet fans represent an ideal tool for supporting natural ventilation. They can be installed in side niches and can be activated in very short time in either direction whenever needed. Optimum control requires an appropriate monitoring of the internal and external temperature and flow rate through the facility. Based on this, natural buoyancy can be exploited to its maximum potential.

The price to be paid for the excellent energy efficiency of such systems is the need for appropriate system's control and understanding. Optimum operating conditions vary seasonally and sometimes even during day. The operating modes of the ventilation system need to be adapted accordingly.

Forced ventilation generally requires large ventilation stations. The full airflow required by the facility needs to be led through the fans, which requires large machines. The installation requires dedicated shafts or tunnels closed on both sides of the fans by separating walls and doors. Ancillary installations, such as silencers and air locks, require additional space and increase the overall costs. Additionally, such systems intrinsically suffer from very high system losses, resulting in large power requirements. Forced ventilations generally impose a fixed ventilation direction. Thus, the fans operate against the natural circulation during a significant fraction of the time. Finally, and most serious, because of the large losses intrinsic in such systems, they generally must be operated permanently. This combination of large pressure losses and permanent operation results in very large operational costs.

The advantages of ventilation systems using jet fans for supporting natural ventilation can be summarized as follows:

- Low investment costs
- Low operational cost, because of the simplicity of the system
- Low energy consumptions, because of the low installed power and reduced number of operating hours
- Full accessibility and minimum space requirements
- Reduced problems in case of ordinary maintenance
- Full operational flexibility

Generally speaking, such systems can provide excellent energy efficiency and should be considered in all situations, where natural ventilation is "almost" sufficient. Such conditions are met very frequently in practice.

As discussed, the proper selection of the ventilation system is essential for achieving optimum energy efficiency. Further optimization steps should be considered as well, including:

- Proper fan selection, for achieving best performance around the most common duty points
- Variable operation regimes through frequency converters
- Consistent aerodynamic design of the whole system
- Appropriate ventilation control, based on appropriate sensors and closed-loop automated control algorithms.

Last but not least, ventilation in normal operating conditions should not attempt at achieving the best-possible air quality but should focus on adequate objectives e.g. in terms of air quality, temperature of humidity.

6. SAFETY IN CASE OF FIRE

Safety is a key requirement for any underground facility and plays a fundamental role in ventilation design. But this is not the focus of this paper. For this reason, this fundamental topic shall be handled in a brief manner.

In case of fire, it is frequently very useful having the possibility of reversing the ventilation direction, for supporting the most appropriate self-rescue or intervention strategy. This can be achieved with appropriate ventilation design. In case of natural ventilation, it should be critically verified, if this is really a requirement. Fire detection generally takes time in complex underground infrastructures. This leads to a more or less extensive smoke propagation before detection. Under such conditions, flow reversal is generally not the preferred option, because it significantly increases the extent of smoke propagation and blocks access to the fire from both directions. Moreover, since fire location is generally not accurately known, the potential for optimizing the fire-ventilation strategy is frequently quite limited.

Systems without flow reversal should account for two separate ventilation directions. The optimum self-rescue scenario depends therefore at least on fire location, occupant's location and flow direction. The same applies for intervention. Such dynamic safety systems can be easily built based on digital technologies and dynamic escape signalization.

7. CASE STUDY – SCHOLLBERG QUARRY

The underground quarry Schollberg in Switzerland, extracting 100'000 m³ of limestone per year, has a room and pillar layout with cavern cross section of 216 m² (Figure 8, Figure 9 and Figure 10).

Figure 8 External installations of the Schollberg facility

The facility has two main connections to the surface, located roughly at the lower and upper end of the building visible in the left-hand side of Figure 8. The elevation difference is about 70 m, and the internal temperature is fairly constant around 12°C. The average monthly external temperature varies roughly between 0°C and 20°C. Daily values obviously exceed these bounds in both directions. This is sufficient for inducing a powerful seasonal air circulation in the whole system (Figure 11), characterized by:

- a winter cycle, where the air enters the lower portal and leaves the system from the shaft and
- a summer cycle, where air circulates in the opposite direction.

Figure 9 Impression of the interior of the Schollberg facility

As expected, natural ventilation is perfectly adequate during the hot and cold seasons but insufficient during the intermediate seasons. The system was analyzed based on one-dimensional and three-dimensional simulation. The main steps were as follows:

- Investigation of the general aerodynamic characteristics of the system (typical summer and winter situations) and quantification of the potential of natural ventilation by means of a one-dimensional network solver used for modeling the main natural air circulation patterns.
- Investigation of different options for supporting the natural circulation and improving air distribution during spring and fall.
- Optimization of the air distribution at critical locations by means of detailed three-dimensional flow simulations.
- Experimental verification of the system's effectiveness on site.

The analysis showed that natural ventilation has a very large potential but needs to be supported at times, where the environmental conditions lead to neutral situations with low or no air circulation. A very energy-efficient ventilation system could be designed based on the following elements:

- Installation of automatic air locks at four strategic locations, for preventing direct air circulation between lower entrance and ventilation shaft.
- Installation of two jet fans inside the ventilation shaft for supporting natural ventilation in the intermediate seasons.
- Installation of an automatic measurement system for internal and external temperature and airflow at critical locations.
- Installation of a control system allowing for optimum ventilation control.
- Installation of small mobile fans at strategic locations within the network, for optimizing the air distribution depending on the specific working sites.

This ventilation system efficiently supports natural ventilation allowing for proper air distribution under all circumstances, solving most air quality issues the system experienced during part of the year. Moreover, energy consumption could be minimized by consistently taking advantage of natural air circulation.

It is important noticing, that this ventilation system requires consequent attention for achieving best results. Installation and parameter adjustment require constant monitoring and discipline on the operator side. The optimization of such systems, for achieving optimum environmental performance and reliability, required time and the active involvement of all stakeholders.

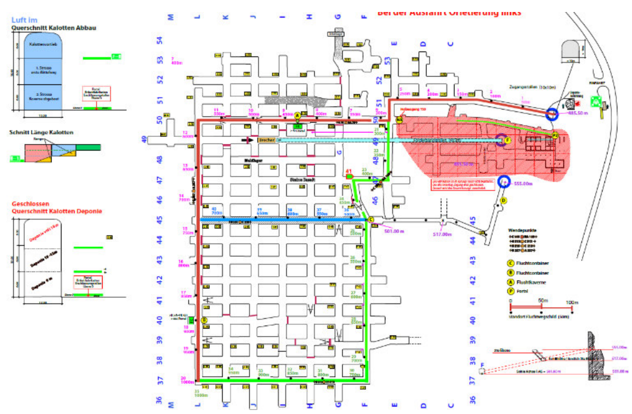

Figure 10. Overview of the Schollberg facility in Switzerland (the main dimensions are about 200 x 500 m)

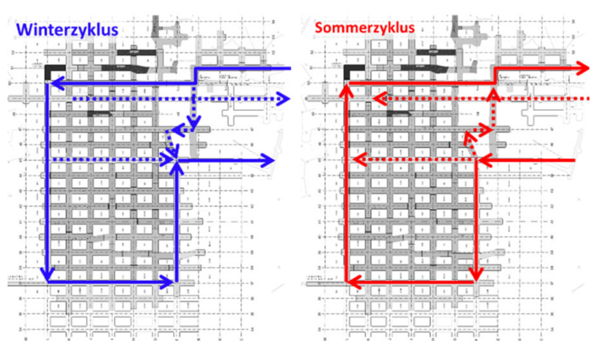

Figure 11 Winter and Summer cycle in the Schollberg

Figure 12 shows the jet fans used as the major active ventilation measure. They have a static thrust of about 600 N with 20 kW motor power and are equipped with frequency converters. Power requirements are very low, and the system could be installed in an existing side niche without additional space requirements or reduction of accessibility. Issues related to power supply, frequently critical in such facilities, could be minimized because of the very low installed power.

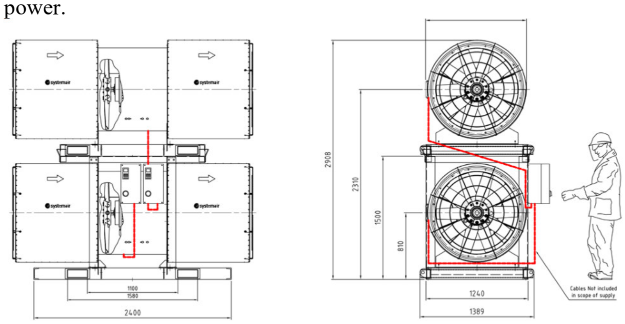

Figure 12 Jet fans for supporting natural ventilation

For comparison, the same objectives can be achieved using forced ventilation. In this case, axial fans with the following key data are required: 100 m^3/s, 750 Pa and about 100 kW power requirements. The required installation volume is roughly 4-5 x 4-5 x 20 m. The high pressure level required is particularly important and largely results from the intrinsic losses of such a system. As mentioned earlier, the fact that a forced ventilation needs to be operated in a virtually continuous manner further increases the gap in terms of energy efficiency between the two systems.

8. CONCLUSION

Energy consumption resulting from the operation of ventilation systems generally represents an important share of the operational costs and environmental footprint of underground facilities. Careful optimization is therefore required for achieving a satisfactory level of environmental sustainability. Natural ventilation resulting from natural temperature differences between the system's interior and the environment, should be used to the largest possible extent.

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