Avanced modeling for the control of tunnel ventilation during excavation and operation

Romano Borchiellini*
Sara Cosentino**
Vittorio Verda*

* Politecnico di Torino,
Dipartimento Energia, Torino
** SPEA Engineering S.p.A, Milano

Innovative tools are necessary to obtain the optimal operating conditions of the ventilation systems in a reasonable lapse of time and accurately. This can be achieved both with appropriate numerical approaches to the full domain as the model order reduction techniques and with the domain decompositions methods as the multi-scale physical decomposition technique. The reduced order mode techniques such as the Proper Orthogonal Decomposition – POD are based on the snapshots method, which provides an optimal linear basis for the reconstruction of multidimensional data. The physical decomposition achieved through multi-level approaches uses the accuracy of the Computational Fluid Dynamics – CFD code in the near field, e.g. the region close to the fire source, and takes advantage of the low computational cost of the 1-D model in the region where gradients in the transversal direction are negligible. In this paper, the features of these two approaches when applied to the control of tunnel ventilation systems are presented. In particular, the use during construction the phase and during operation are discussed.
***Keywords**: simulation models, multi-scale, reduced models.*

***Modellazione avanzata al servizio del controllo della ventilazione di gallerie in scavo ed in esercizio.** L'analisi di condizioni di funzionamento ottimale dei sistemi di ventilazione richiede l'utilizzo di strumenti di simulazione innovativi, capaci di ottenere risultati accurati con ridotti tempi computazionali. Questo può essere ottenuto con tecniche numeriche che coinvolgano la riduzione d'ordine del modello o con metodi di decomposizione del dominio. Tecniche di riduzione d'ordine come il proper orthogonal decomposition – POD sono basate sul metodo degli snapshots, che forniscono una base lineare ottimale per la ricostruzione di dati multidimensionali. La decomposizione fisica ottenuta con approcci multiscala utilizza invece l'accuratezza dei codici termofluidodinamici nel near field, cioè la regione in vicinanza dell'incendio ad esempio, e sfrutta il basso costo computazionale di modelli monodimensionali nella regione in cui i gradienti in direzione trasversale sono trascurabili. In questo articolo sono illustrate le caratteristiche di questi due approcci applicati al controllo di sistemi di ventilazione. Nell'articolo si discute l'applicazione di queste tecniche alla ventilazione ordinaria in fase di costruzione e alla ventilazione di emergenza in fase di funzionamento.*
***Parole chiave**: modelli di simulazione, multiscala, modelli ridotti.*

***Modélisation pour le contrôle de la ventilation de tunnels en excavation et en opération.** L'analyse des conditions de fonctionnement optimales des systèmes de ventilation nécessite l'utilisation d'outils de simulation innovants, capables d'obtenir des résultats précis avec des temps de calcul réduits. Ceci peut être réalisé avec des techniques numériques impliquant la réduction de l'ordre du modèle ou avec des méthodes de décomposition du domaine. Les techniques de réduction d'ordre telles que la proper orthogonal decomposition – POD sont basées sur la méthode des instantanés, qui fournissent une base linéaire optimale pour la reconstruction de données multidimensionnelles. La décomposition physique obtenue par des approches multi-échelles utilise plutôt la précision des codes dynamique des fluides informatisée dans le champ proche, qui est la région à proximité du feu, par exemple, et exploite le faible coût de calcul des modèles unidimensionnels dans la région où les gradients dans la direction transversale sont négligeables. Cet article décrit les caractéristiques de ces deux approches appliquées au contrôle des systèmes de ventilation. L'article traite de l'application de ces techniques à la ventilation ordinaire pendant la construction et à la ventilation d'urgence pendant le fonctionnement.*
***Mots clés**: modèles de simulation, multi-échelle, modèles réduits.*

1. Introduction

1.1. Simulations for ventilation control

Complexity of tunnel systems is increasing, with more and more stringent constraints related with safety conditions, operational costs, environmental issues, etc. One of the most important parts which is affected by this evolution is the ventilation system. Its complexity is also increasing, during the design phase, but especially during operation. In this framework, ventilation settings and adjustments often rely on simulations able to provide a detailed representation of the scenario depending on the variation in the control parameters. Nevertheless, simulations typically require large computational resources, which make often difficult to comply with the requirements for control application. A possible option to combine together the accuracy of detailed models and small computational time consists in the application of reduced models. This paper aims at showing how reduced models can be effectively applied to tunnel ventilation control. Two approaches are considered: proper orthogonal decomposition and multi-scale models. Their features are briefly introduced in this section, while the applications to tunnels are shown in sections 2 and 3, respectively.

1.2. Proper orthogonal decomposition – POD

Proper orthogonal decomposition – POD is one of the most

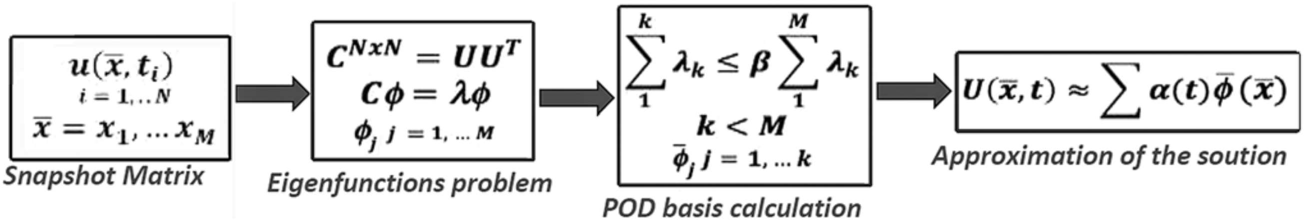

Fig. 1. POD procedure.
Procedura POD.

widely known model order reduction techniques used to simplify the simulation of dynamical systems described by differential equations. This is a posteriori reduction method, which is based on the extraction of the essential information from the full model and its reduction to a more compact model. Consequentially, computational costs are significantly reduced while preserving the accuracy.

POD is applied in several fields, such as the images processing [1] analysis of turbulent fluid and multiphase flows [2], unsteady aerodynamic flows [3] and many others.

POD model is built using the method of snapshots proposed by Sirovich [4]. The method provides a parametric fit of a set of given multidimensional data by constructing an appropriate expansion series and its coefficients. POD extracts both the interpolating functions and the coefficients from the information contained in the data set. A schematic of the full procedure is shown in figure 1.

1.3. Multi-scale models

Computational Fluid Dynamics – CFD is largely used as an engineering tool for the analysis of both normal operating conditions and in the case of fire. This relies on the numerical solution of the three-dimensional unsteady form of the conservation of mass, momentum and energy. As a result, the velocity and temperature fields, as well as the species concentration can be obtained. The accuracy of CFD significantly depends on the size of the computational grid which is used for the domain discretization. This involves the use of a sufficiently dense mesh, which may lead to unsuitable computational costs in the case a vast domain should be explored. CFD becomes thus unsuitable for the simulation of network infrastructures, which might be several kilometer long. For this reason, the computational domain is often limited to a small region i.e. close to the fire and the velocity and temperature profile in the rest of the domain are assumed as known.

The use of 1D models solves the problem of high computational costs of CFD thanks to complete and compact description of the system of interest. In 1D modelling, flow is assumed as homogeneous in each cross section making 1D models unsuitable to simulate the fluid behaviour in regions where high gradients occur. Proper corrections and empirical correlations must be introduced to account the tri-dimensional behaviour of flow in such regions, which constitute a source of large uncertainties especially in the case of application to fire events.

Multi-scale methods, based on hybrid 1D-3D computational techniques, have been proposed with the goal of contributing to overcome the issues related with both 1D and 3D models. Multiscale approaches consist in a physical decomposition of the domain in two or more sub-regions, each one assigned with different modelling complexity: 3D models are used only in the zones where large transversal gradients occur and need to be calculated; 1D models are basically used to link the 3D volumes with the surfaces where realistic boundary conditions can be imposed. This technique allows one keeping the accuracy of results typical of 3D models, with a computational cost closer to that of 1-D models. For further details, see [5, 6].

2. Application of POD models to the sanitary ventilation during tunnel construction

2.1. Model of sanitary ventilation

One of the main roles of ventilation consists in keeping suitable ambient conditions inside the tunnel. This is necessary to the workers during tunnel excavation, and to the end-users and operators during normal operation. The contaminant concentration inside the tunnel can be expressed by equation 1:

$$\frac{\partial C^*}{\partial t^*} = \frac{1}{Pe}\frac{\partial^2 C^*}{\partial x^{*2}} - \frac{\partial C^*}{\partial x^*} + S_p^* \qquad (1)$$

where:
- $C^* = \frac{C - C_{min}}{C_{max} - C_{min}}$ is the non-dimensional form of the concentration, being $C_{max} - C_{min}$ the

range concentration between the minimum and the maximum;

- $x^* = \frac{x}{L}$ is the non-dimensional form of longitudinal coordinate, being L the tunnel length;
- $t^* = t\frac{u}{L}$ is the non-dimensional form of the time, being *u* the longitudinal air velocity due to the forced air flow;
- *Pe* is the Peclet number;
- $S_p^* = \frac{S_p * L}{\Delta C * u}$ is the non-dimensional form of the pollutants source, i.e. the excavation processes during construction and the car engines during normal operation.

The initial condition is given by natural concentration of contaminants in the air (e.g. 5 ppm in the case of NO_x). Concerning the boundary conditions, a Direchlet condition, indicating the external concentration, is prescribed on the external portals with inlet flow and a Neumann condition, indicating pure convective transport, is prescribed on the external portals with outlet flow. Results of the model application to the NO_x concentration during the excavation phase of a rail tunnel in Spain are shown in figure 2. In the figure, both the model results and the experimental measurements are shown during eight hour period.

The application of POD to equation (1) generates a very flexible modeling approach, which can be applied to a tunnel with variable length, as it occurs in the case of tunnel excavation. The model provides the distribution of contaminant concentration as the function of the air velocity, i.e. the ventilation flow. The maximum deviation of results is less than 1%, with a reduction of the computational time of about 80%. This makes the model suitable for control purposes, as discussed in the next section.

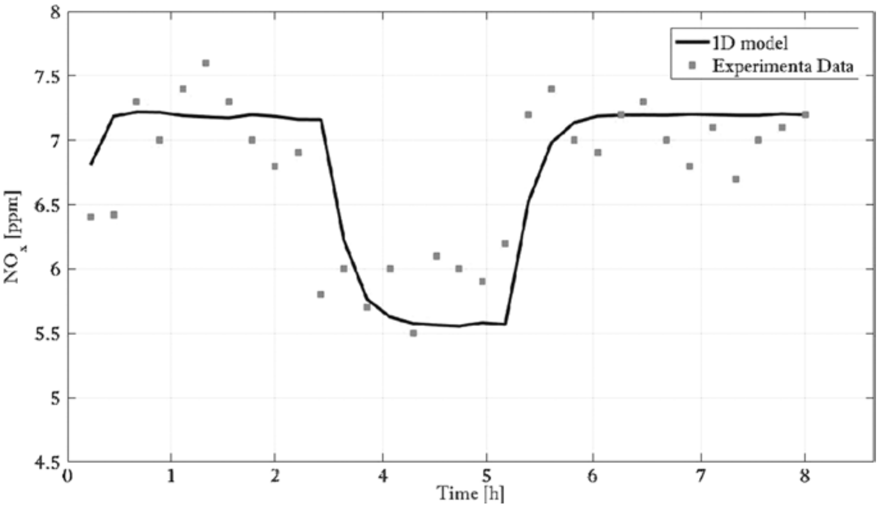

Fig. 2. Comparison of model results and experiments in the application to NO_x concentration during tunnel excavation.
Confronto dei risultati del modello e degli esperimenti nell'applicazione di note concentrazioni di NO_x durante lo scavo di gallerie.

2.2. Application of a POD model to tunnel ventilation control

The proposed POD model can be used to predict the NO_x concentration depending on the various sources (loaders, excavators, trucks etc.) and the tunnel geometry. This can be used within a fuzzy logic control, which aims at minimizing the energy consumption for ventilation, taking into account the NO_x level evolution and considering the time since the last adjustment. This latter requirement is made in order to reduce the number changes in the operating regime of the ventilation fan as much as possible, in order to keep the potential impact of maintenance small. A schematic of the algorithm structure is shown in figure 3. The selected membership functions for the inputs are Gaussian. The linguistic variables of the output (the fan velocity) has a triangular membership functions.

An application of the proposed algorithm and its comparison with the conventional ventilation strategy characterized with constant fan velocity is presented in figure 4. The figure refers to a typical working day during the excavation phase, when the tunnel length was about 1500 m. The use of the fuzzy logic algorithm allows one to reduce the electricity consumption of about 24%, keeping NO_x within the acceptable limits. In addition, the number of fan adjustments is limited.

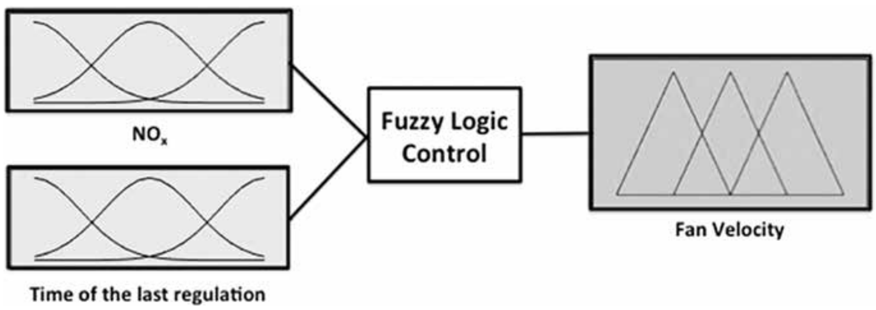

Fig. 3. Schematic of the fuzzy logic algorithm for ventilation control.
Schema dell'algoritmo di logica fuzzy per il controllo della ventilazione.

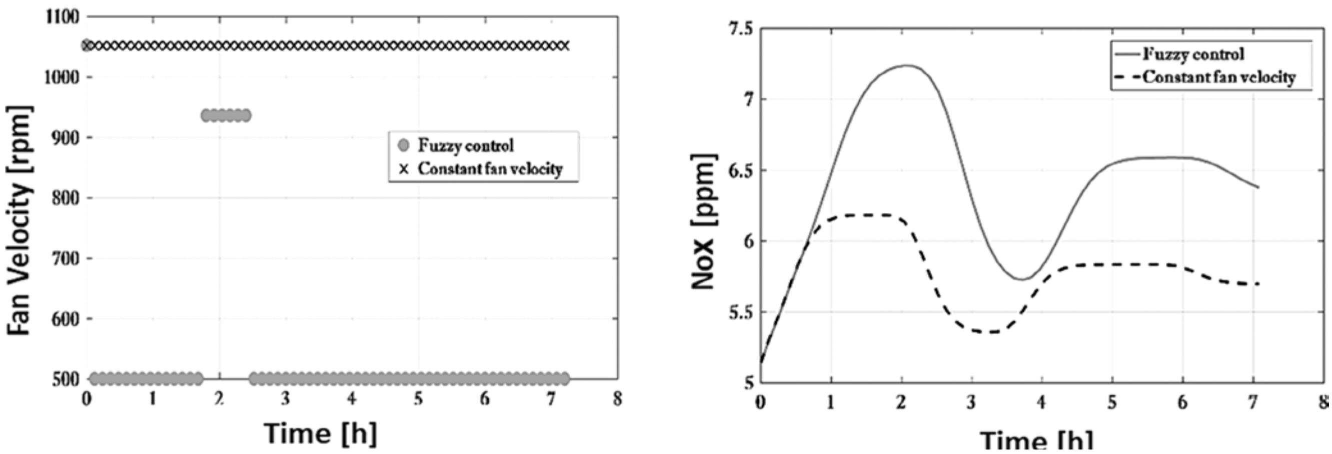

Fig. 4. Comparison between fuzzy control and constant velocity in the application to tunnel excavation.
Confronto tra controllo fuzzy a velocità costante nello scavo di tunnel.

3. Application of multi-scale modeling to emergency ventilation

3.1. Multi-scale modeling of tunnels

The multi-level approaches based on non-overlapping domain decomposition can be used to model complex systems as the underground infrastructures (tunnels road, mines and sub-way stations) and to study the ventilation systems both in sanitary and emergency conditions. As already mentioned, it consists in dividing the domain in sub-regions, each described through a model of proper complexity. The choice of such complexity depends on the phenomena which should be considered. Several studies on the flow fields in underground infrastructures show that in the portion of the domain close to jet fans or to the fire, the flow has a complex 3D behavior with velocity, concentrations and temperature gradients. This region is called the near field and should be modelled considering 3D geometry in order to properly capture the phenomena. The remaining portion of domain is called the far field can be described by 1D model. In fact, the various quantities show an almost homogeneous distribution in the transversal directions, while the gradients in the longitudinal direction are prevalent. A schematic of a multi-scale model is shown in figure 5.

This scheme allows the accuracy of results typical of CFD-3D in the near field and the low computational cost of the 1-D models in the far field. The congruence of the simulation is guaranteed by a continuous exchange of information at each interface, where a Dirichlet-Neumann coupling strategy is applied. Considering a specific boundary surface (i.e. a surface in the 3D model and a node in the 1D model), the 3D imposes one type of boundary condition (e.g. Dirichelet) to the 1D boundary node while the 1D simulation is performed, and the 1D imposes the dual type (Neumann in our example) to the boundary surface while the 3D simulation is performed. The results reported in the next section refer to the implementation of this type of strategy obtained by integrating the CFD open code FDS and the 1D code Whitesmoke, developed within the Energy Department at Politecnico di Torino.

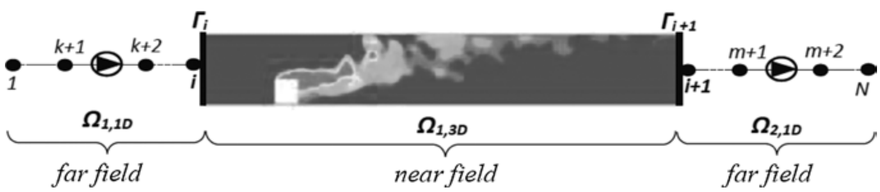

Fig. 5. Schematic representation of a multi-scale structure for tunnel ventilation analysis.
Rappresentazione schematica di una struttura multi-scala per l'analisi della ventilazione del tunnel.

3.2 Application of the multi-scale model to the simulation of a fire event

An application of the multi-scale to the simulation of a fire scenario in the Monte Cuneo tunnel, located near Torino, is presented in this section. The tunnel is 1906 m long, with a cross section of 66 m^2 and has a positive slope in the first part (1.79% slope for 846 m from North gate) and a negative slope in the second part (-2.65% slope for 1060 m). The tunnel uses a semi-transversal ventilation system, with 18 extraction dampers, which are remotely controlled. Four dumpers open in the case of fire and extract smoke in the fire zone. Four jet-fans are used in order to balance possible pressure differences between the portals. The schematic representation of the multi-scale model is similar to that shown in Fig. 5. The full domain of the tunnel is split in 3 sub-regions: two *far fields* modelled by the network of 9 nodes and 8 branches each one and one *near field* in 3 dimensions. This portion of roadway in FDS is located between 1D nodes N09 and N15. It is 369 m with the fire in the center position and the four correspondent open dampers located upstream and downstream the fire. In the 3D model, a vehicle burning in the center of the tunnel has been considered. An Heat Release Rate - HRR of 30 MW has been considered, with a trapezoidal shape, derived from experimental results [7]: 10 min growth ramp, 40 min steady state and 20 min decrease ramp.

In order to simulate the air/smoke extraction, four surfaces have been created in the upper part of the 3D computational domain, in correspondence to the dumpers. The extracted mass flow rate has been imposed as a boundary condition. The 4 accelerators and the axial fans have been modelled in the 1D network taking into account their characteristics curves [8]. The effect of deflectors has been obtained by shifting the curve, so that the nominal pressure rise increases from 3.5 Pa to 6 Pa.

Figure 6 shows the average longitudinal air velocity which is obtained at steady state, in a critical condition. The zero velocity is located within the extraction area converging velocities are obtained on both sides. This means that smoke tends to converge towards the extraction zone. With respect to the jet fan operation without deflectors, the volumetric flow rate difference between the two portals decreases significantly. The air velocity at the North gate, which was close to zero, increases to about 0.5 m/s thus making the operating condition more balanced.

A better description of the ventilation system performance is provided by the results of the 3D model. Figure 7 shows the smoke propagation during the event evolution. For t<600s, smoke occupies almost the entire roadway. When the HRR reaches its maximum, smoke is pushed towards the North side. Some smoke back-layering is also observed.

The corresponding temperature field in the longitudinal plane located at the center of the roadway is shown in Fig. 8. The maximum temperatures near the ceiling are below 500 °C. This represents a decrease with respect to the configuration without deflectors and reduced dumpers. This is particularly positive to guarantee safe operating conditions to the axial fan, which should be maintained below 250°C for two hours in case of emergency. In this case, the

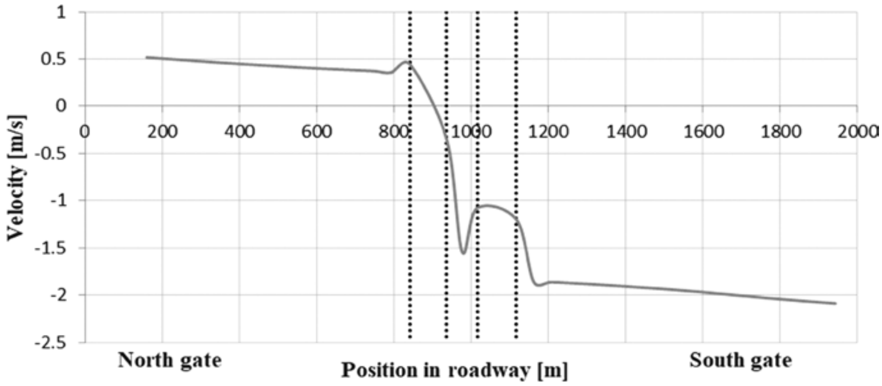

Fig. 6. Mean longitudinal velocity in the roadway in the re-design configuration.
Velocità longitudinale media nella carreggiata nella configurazione di riprogettazione.

Fig. 7. Smoke propagation at different time step in the re-design configuration.
Propagazione del fumo in tempi diversi nella configurazione di riprogettazione.

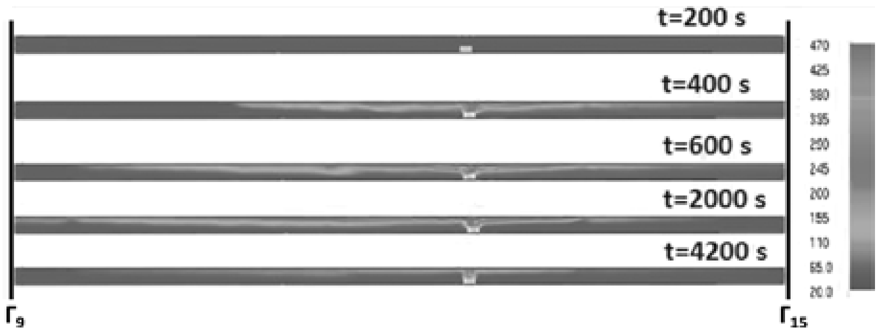

Fig. 8. Temperature distribution in the smoke are in the re-design configuration.
La distribuzione della temperatura nel fumo è nella configurazione di riprogettazione.

extraction temperature is always lower than 240 °C for the entire simulation time.

With respect to simulations performed considering full extension of the 3D geometry to the full domain, a significant reduction of the computational time (of more than 80%) is obtained.

4. Conclusions

In this paper, two possible modelling techniques that can be applied to the analysis of ventilation control in tunnels, in the case of both sanitary ventilation and emergency ventilation. The first method is the proper orthogonal decomposition. This is here applied to the optimal control of the ventilation system for a tunnel under excavation. The second method is the multi-scale model. The application to the simulation of a fire event and the corresponding ventilation strategy is proposed. In both cases, a large reduction of the computational time is obtained with practically no significant effects on the simulation results.

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