CFD-ASSISTED FLOW RATE MEASUREMENTS IN VENTILATION DUCTS OF LONG ROAD TUNNELS

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ABSTRACT

Large-size air ducts with irregular cross section, such as the ventilation channels of road tunnels, offer formidable difficulties in the measurement of the flow rate. Despite a large bulk of experiences, the measurement techniques developed so far are not completely satisfactory in terms of accuracy or repeatability. Moreover, technical standards only consider very simple cross-section shapes, and prescribe the adoption of a prohibitive amount of measurement points. This motivated the development of an alternative technique for the reconstruction of the air flow rate, where the signals from a custom-built, multi-point measurement rig composed of 16 Pitot-Prandtl tubes are supported and integrated with Computational Fluid Dynamics (CFD) predictions. The technique was tested on two cross-sections of the extraction line in service at the Mont Blanc Tunnel (TMB). Preliminarily, CFD analyses were performed over a range of Reynolds numbers typical for that application. These were used to post-process the point-velocity data collected on field and to reconstruct the flow rate. Results of the testing campaign are presented here, along with a general description of the technique. Preliminary outcomes of the tests are encouraging and indicate that the present approach could be applicable to a larger variety of case studies.

Keywords: tunnel ventilation; smoke extraction; flow rate measurement; CFD; Pitot tubes.

1. INTRODUCTION

The development of an original technique for multi-point velocity rigs was imposed by the demand of measuring with sufficient accuracy the air flow rate in the extraction circuit of the Mont Blanc Tunnel (TMB) in case of fire. The TMB extraction line consists of a channel, with variable and irregular cross-section, running along the entire tunnel under the road deck, consisting of two branches, on the French and the Italian sides, respectively, joining near the half of tunnel length. Vitiated air is extracted from a series of on/off extraction vents, located each 100 m on the tunnel ceiling. In the case of an event, 7 extraction vents open, for a total length of 600 m centered on the fire, and the channel is depressurized by a couple of centrifugal fans at each end. The airflow extracted through the vents from the tunnel ceiling splits in two once in the channel, a certain percentage flowing towards the French station and the rest towards the Italian one (Fig. 1), depending on the atmospheric conditions and on the position of the event. The strategic importance of this safety line does not need to be stressed and for this reason TMB-GEIE, the concessionary binational company of the infrastructure, commits periodical checks of the extraction rate to specialized companies.

The problem of detecting the air flow rate in irregular ducts of large size dates to the XIX century, in the context of mine excavation safety rules [1]. In the case of large and irregular sections only techniques falling in the class of the "velocity-area methods" are practically viable. These techniques can be classified as: (i) single-point methods, where the flow rate is retrieved from a single velocity signal to be multiplied by the section area; (ii) continuous traversing methods, where a single velocity probe is moved through the duct section, and velocity values are averaged to give the mean air-velocity; and, (iii) multi-point methods, where the duct area is subdivided into a number of sub-areas at the centers of each the air velocity is measured. The volumetric flow rate in the duct is built-up by summation of all the (velocity x area) contributions.

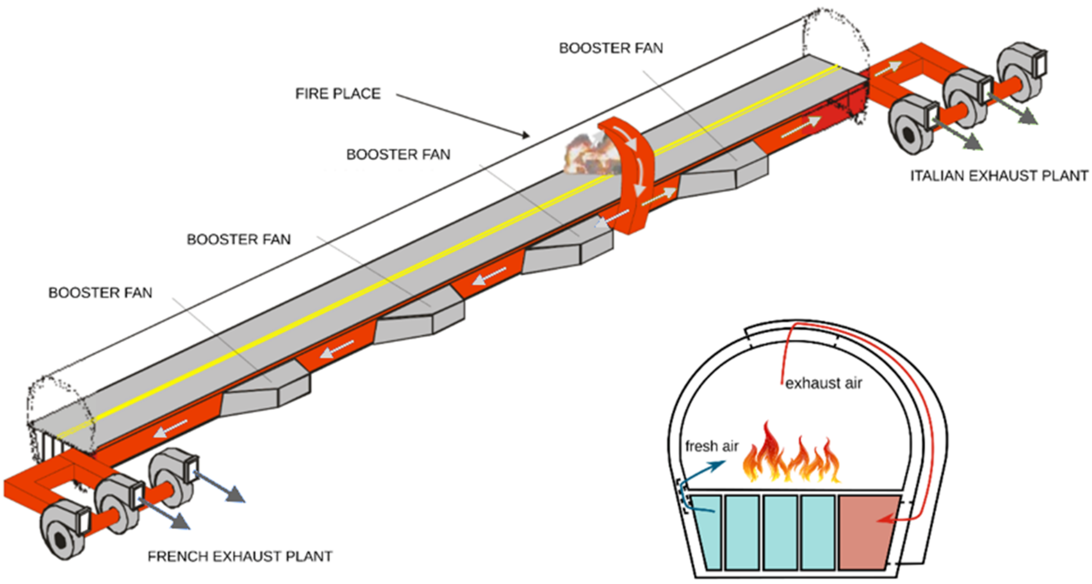

Figure 1: Schematic of the TMB extraction system (courtesy of TMB-GEIE) and typical cross-section of the tunnel and ventilation channels

In single-point measurements a correction factor must preliminarily be determined, to account for the non-uniform velocity distribution along the duct section [2]; such a factor may depend on the type of velocity probe, the presence of an operator, the data collection technique, but also depends on the total flow-rate, i.e. the Reynolds number, and, most of all, on the specific duct geometry. Continuous traverse methods are expected to be more accurate than static single-point measurements in the experimental reconstruction of the mean velocity in non-standard shape tunnels. Since the complete sweeping of a large section takes time, the method reliability decades if unsteady conditions affect the flow [3].

Multi-point methods are generally considered to be superior, in terms of accuracy and reliability, to single-point and continuous traverse methods. In this context, the problem arises of optimizing the number and the positions of the velocity probes over the duct section. Two schemes for determining the grid of locations where measurements should be taken have been credited for rectangular ducts in the context of HVAC systems. These are the Equal Area and Log-Tchebycheff distributions. In the latter case, the grid-points are unequally spaced with the external points close to the walls to account for the wall-friction effects, as opposite to the Equal area distribution, where the section is subdivided into equal square or rectangular sub-areas. The experimental comparison of the two methods carried out by Klaassen and House [4] however demonstrates that the two distributions are, in general, equally consistent.

On the other hand, no technical directions are available relative to the number of velocity sensors and their relative positioning on a section of irregular shape: ISO Standard n.7194 [5] only considers circular ducts; ISO Standard n.5802 [6] includes square, rectangular, annular, elliptical, oval, octagonal, and trapezoidal sections. The number of probes needed for an accurate estimate of the flow rate in a non-circular duct is in any case very high. For example, for a rectangular section, a 49-point rake is prescribed over a properly distributed 7x7 grid [6]. It is therefore obvious that sections of irregular shape would demand clusters of 100 probes or more. In practical terms, numbers of velocity probes of that order imply the risk of blockages, high costs, and excessively long times of setting-up of the experiments, often incompatible with the operational constrains of a tunnel. For the above reasons, a limited number of measuring points has been used in all the cases considered in the literature [7-10].

Despite such a considerable number of experiences, the methods developed so far appear as not completely satisfactory, either in terms of accuracy or of repeatability. This motivated the development of an alternative technique of reconstruction of the air flow rate, where the signals from a multi-point measurement rig are post-processed by means of CFD predictions. In the case of concern here, the use of multi-point procedures was dictated not only by the need of accuracy and repeatability of the measurements, but also by the impossibility of accessing the ducts under operative conditions. To overcome the drawbacks of the classic velocity-area methods an accurate pre-analysis was carried out to verify the possibility of integrating the point-velocity data with numerical predictions by CFD. This gave rise to the design and realization of two 16-probe clusters. As detailed below, a large CFD-prediction data set was created and this was used to build-up the entire axial velocity profile over the section, based on the measured velocity values. In this way, using a relatively low number of sensors, it was possible to account for the complexity of the velocity distribution and to derive more reliable estimates of the flow rates. The technique was finally tested in the two branches of the extraction line of TMB, and results from one of the first testing campaign are presented here and discussed.

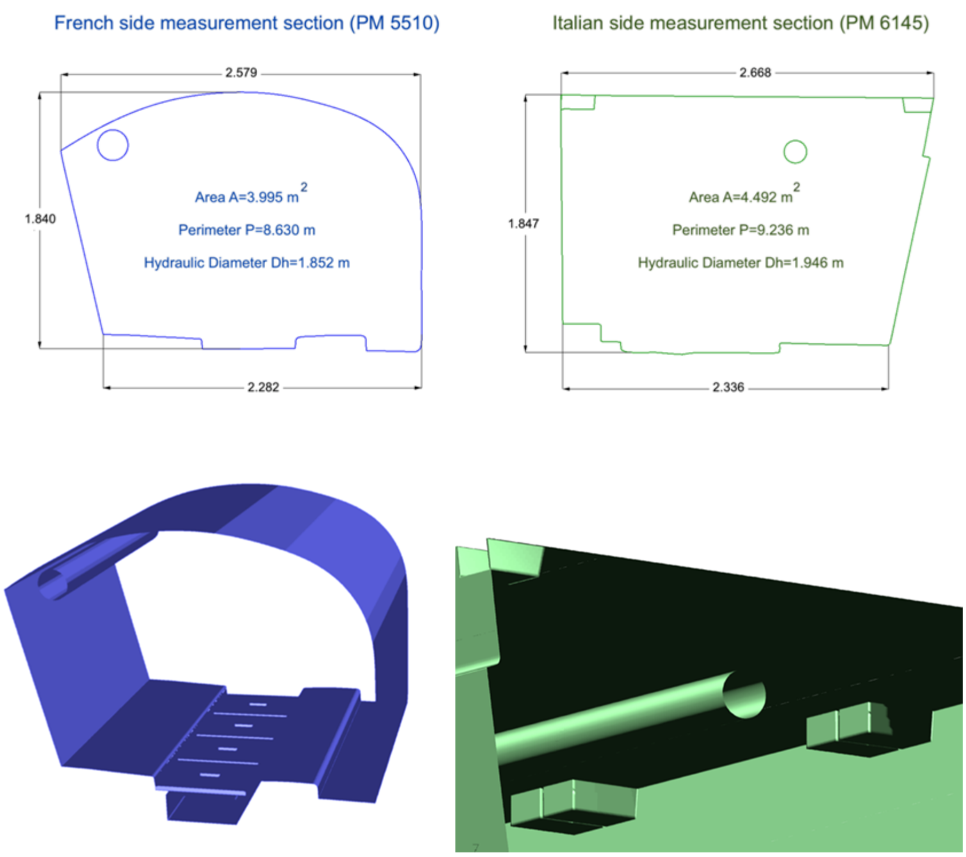

Figure 2: (above) measurement sections in the TMB extraction channel: French side (left) and Italian side (right); reconstruction based on laser scanner data; (below) details of the 3D model showing service pipes, drains and other structural elements.

2. CASE STUDY

In addition to practical issues due to measuring in such an infrastructure, the operative difficulties the task presents are formidable and demand specific solutions to be developed.

One first problem is given by the large size and the variable geometry of the dimensions of the duct section. Assuming an event at the mid-point of the tunnel, two sections were identified immediately outside of the extraction area where the channel geometry is sufficiently regular, with approximately constant cross section, and far away from any important upstream obstacle, to avoid possible wake effects.

The two sections, located at metric points PM5510 and PM6145 (considering as origin PM0 the French portal) are irregular, different in shape and size and result to be multi-connected due to the presence of a longitudinal drainage pipe, as represented in Fig. 2.

3. NUMERICAL ANALYSIS

The numerical activity relied upon the use of the CFD Finite Volume code OpenFOAM v7. The flow was assumed to be incompressible and steady state. The flow-field was assumed to be fully turbulent, and the RANS (Reynolds Averaged Navier-Stokes) approach enforced. Three alternative turbulence models were selected among the most popular and validated for this type of applications. In particular, the k-ω SST (Shear Stress Transport) model, the realizable k-ε model, and the Reynolds Stress Model (RSM) were tested and compared.

Two series of preliminary simulations were carried out: the first on a simplified geometry but with similar flow structures (square section) to validate the numerical procedure and to derive general guidelines for grid convergence, the second on real sections (Fig. 3) with increasing level of detail for final assessment of the numerical procedure on the real case.

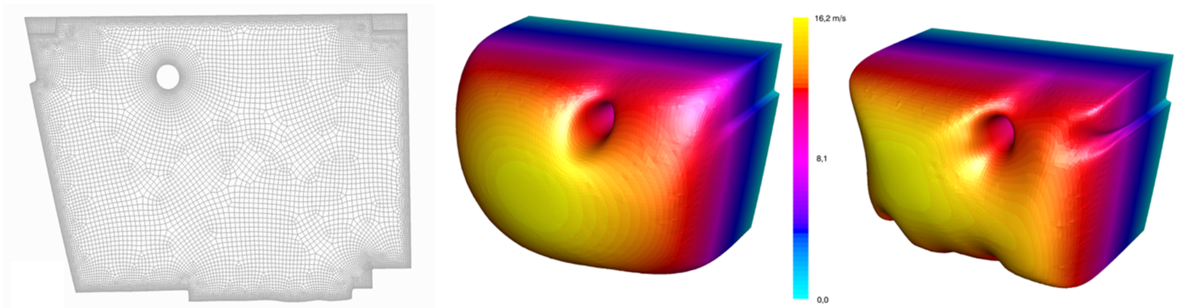

Figure 3: (left) final mesh adopted for the cross section of the Italian side (the French one is qualitatively similar); longitudinal velocity profile on the Italian measurement section with the k-ω (center) and RSM (right) models.

4. EXPERIMENTAL FACILITY AND DATA REDUCTION

4.1. Choice of the measurement points

Previous experiments had been carried out over the two sections of the extraction line described above. In those cases, an array of 10 Pitot-tubes was used, arranged on two parallel vertical rows. The volumetric flow-rate values were derived by the crude average of the local velocity signals times the section area. Based on CFD analyses, it was decided to increase to 16 the number of probes on each section, complementing the 10 original positions, that were conserved for the sake of comparison, with 6 additional probes located on a single horizontal row. The geometry of the two probe-arrays is shown in Fig. 4.

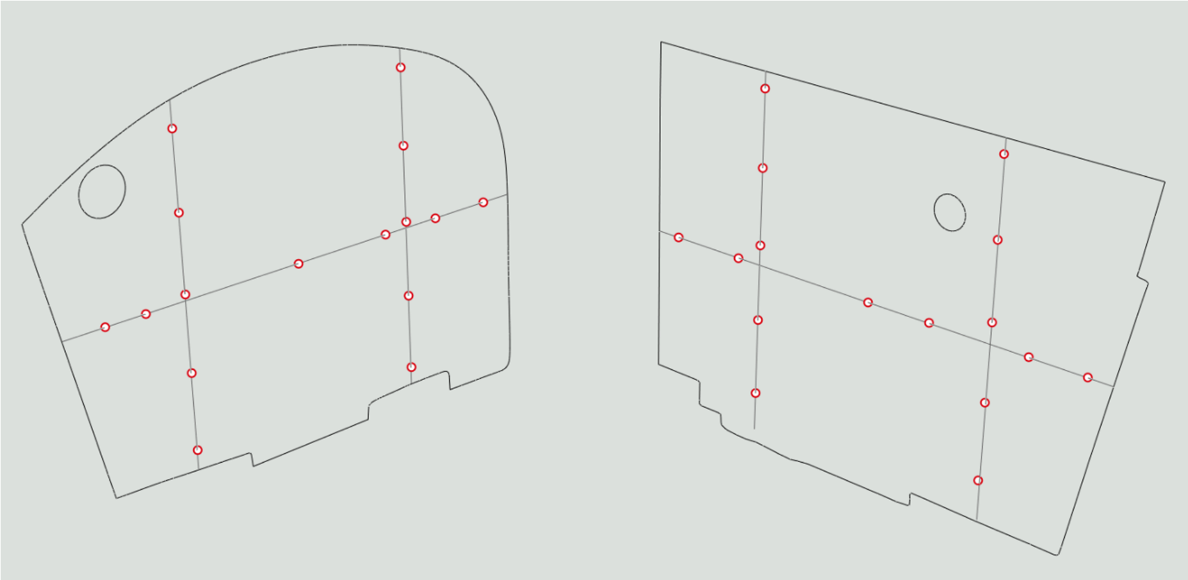

Figure 4: qualitative distribution of the measurement points on the French (left) and Italian (right) sections.

4.2. Experimental rig

8 mm NPL-type Pitot probes were adopted for velocity measurements in accordance with ISO3966, Annex A [5]. The design of the two arrays was directed to minimize as much as possible the aerodynamic influence of the rigs, while ensuring accurate and repeatable measurements. Extruded aluminum alloy hollow beams with low aerodynamic impact (NACA0009 profile) were adopted for the holding structures and the 32 pressure lines pass inside the beams, sort out at the foot of the vertical bars, and connect to the pressure scanner, positioned several meters downstream. Each pressure scanner is equipped with two series of 8 differential pressure transducers with different full-scale value (250 Pa was chosen for the central probes and 160 Pa for the peripheral probes, closer to walls) with an accuracy of ±1.75% of the full scale. The dynamic pressure data are complemented with the measurement of local temperature, absolute pressure, and relative humidity, needed for an accurate estimation of the local air density. The sampling frequency for all the measurements was set at 1 Hz. Some geometrical details of the probe and its connection to the support structure are shown in Fig. 5.

4.3. Data reduction

The database provided by the numerical experiments was used to correlate the axial velocity values, as measured at the 16 sampling points, with the mean velocity over the section area, and the total flow rate. The procedure is based on the following equation:

$$\bar{v} = \frac{\sum_{i=1}^{N} f_i(\,v_i)}{N} \qquad (1)$$

Here, $\bar{v}$ and N are the mean velocity and the number of the measuring points over the section (N = 16 for each of the two sections), and $f_i(\,v_i)$ is a function correlating $\bar{v}$ to the local velocity value, v_i. The correlating functions are derived by the numerical predictions, and as expected, they change with the position of the sampling point and the mean-velocity value itself. The accurate estimate of the f_i- functions is a crucial point of the procedure. For example, Fig. 6 presents the 16 functions for the French section with reference to the RSM model. It is immediate to observe that, over the interval of interest for the experiments, all the local velocities correlate linearly with the mean values. Similar trends were obtained with all the three models for both sections.

For the *i-th* sensor the linear trend can be expressed as:

$$v_i = m_i \bar{v} + q_i \tag{2}$$

By dividing by $\bar{v}$ one obtains

$$\frac{v_i}{\bar{v}} = m_i + \frac{q_i}{\bar{v}} \tag{3}$$

Figure 5: details of the Pitot-probes system (above) and general view (below) as installed on the French side.

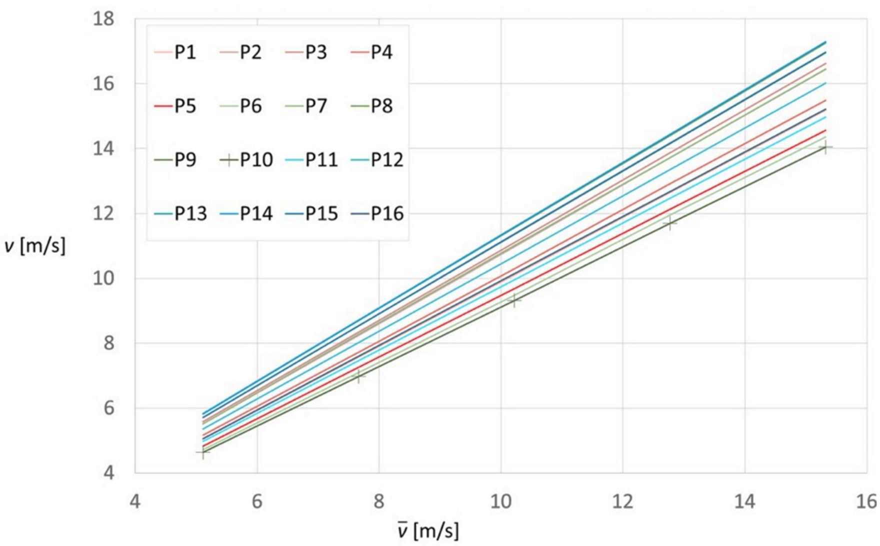

Figure 6: axial velocity vs. mean velocity at the 16 measurement points for the French section (CFD - RSM model).

It is convenient to recast eqn. (3) by introducing into it the Reynolds number, Re

$$Re = \frac{\rho \bar{v} D_h}{\mu} \tag{4}$$

Here, D_h is the hydraulic diameter of the section, and ρ and μ are the air density and viscosity under the actual operative conditions. It is useful to remind that the thermodynamic properties of air encountered in the experiments can differ substantially from the standard values employed in the numerical simulations. Eqn. (3) becomes:

$$\frac{v_i}{\bar{v}} = m_i + \frac{k_i}{Re} \quad ; \quad k_i = \frac{q_i \rho D_h}{\mu} \tag{5}$$

Solving back for $\bar{v}$ we get the final form of the f_i - function to be inserted into eqn. (1):

$$\bar{v} = f_i(v_i) = \frac{v_i}{m_i} - \frac{k_i \mu}{m_i \rho D_h} \tag{6}$$

It is appropriate to point out that the $\bar{v}$- value estimate differs from one measuring point to the other, due to two main reasons: (i) the f_i's are based on numerical predictions, and these can just approximate the real flow-fields; (ii) the local velocity data are affected by uncertainties inherent to the use of the Pitot-probes as well as to the positioning of the sensors and the accuracy of the transducing chain. The final value of the mean velocity, i.e. the one we assume to be the most reliable, is therefore the result of the averaging of the 16 independent estimates of $\bar{v}$, as from eqn. (1).

5. FIRST RESULTS

The technique described above was applied so far 6 times to reconstruct the extraction flow rate at TMB. Results of a testing campaign which took place on July 7th, 2023, are reported in Table 1, in terms of relative deviation with respect to a reference value of the reconstructed flow rate. In this case, the reconstruction using the CFD results obtained with the k-ω SST model is chosen as the reference, since it determined the lowest percentage standard deviation on the reconstructed flow rate among the three turbulence modelling approaches.

It can be observed that the three estimates are characterized by extremely low relative deviations. Obviously, the single reconstructed velocity is crucially dependent on the adopted turbulence model, and significant differences could arise between different models (see again Fig. 2); nevertheless, even using a moderate number of points, the reconstructed values already appear as insensitive of the adopted turbulence model. This corroborates the consistency of the present approach, especially if this is compared to a simple averaging procedure (as reported in Table 1). As a matter of fact, the mean value obtained by averaging is systematically higher than the reconstructed value, indicating the need for a weighting of the values on the different measurement points to account for points in the boundary layer or local anomalies due to the presence of elements like the service pipe in the two sections considered here. Furthermore, standard deviations of the CFD-assisted reconstructions do not substantially deviate from those of the simple averaging procedure, suggesting that the uncertainties linked to potential discrepancies between the numerical and experimental profiles are anyway restrained.

Table 1: results from a sample testing campaign

Model	Flow rate French side (% deviation from ref.)	Standard deviation French side	Flow rate Italian side (% deviation from ref.)	Standard deviation Italian side
k-ω SST (ref.)	-	10.93%	-	14.45%
realizable k-ε	0.10%	11.21%	0.06%	14.96%
RSM	0.00%	10.47%	1.10%	16.24%
mean value	3.55%	9.95%	2.84%	10.25%

6. CONCLUSION

A technique for the reconstruction of the air flow rate in large ducts of irregular size was developed and tested on two cross-sections of the vitiated air extraction channel of the Mont Blanc Tunnel. A custom-built, multi-point rig with 16 Pitot-Prandtl tubes provided velocity measurements which were subsequently processed using correlations derived from CFD. Preliminary results of the testing campaigns performed so far highlight the consistency of the technique and its potential adaptability to other duct geometries. Further analyses will entail a deeper analysis of the error propagation and a finer characterization of the experimental profiles in light of CFD results.

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