COMPLEX COMMISSIONING AND QUANTITATIVE TESTING OF THE GOTTHARD BASE TUNNEL VENTILATION SYSTEM

M. Viertel, Ch. Brander, J. Badde, M. Poloni
Pöyry Switzerland Ltd., Switzerland

ABSTRACT

The new Gotthard Base Tunnel will be opened to train traffic mid-2016. As part of the ventilation concept proofing and thermodynamic tunnel system modelling, as well as the commissioning process of the system, an ongoing series of measurement campaigns was carried out within the course of 3 years.

These commissioning and measurement campaigns include initial start-up of the fans, combined functional tests, leakage and airflow measurements as well as pressure measurements. These tests were carried out for various types of structures within the tunnel. The aim was to provide the proof or validate the assumptions made in the concept phase which are crucial for the dimensioning of the ventilation system and surrounding structures.

The focus in this publication is placed on leakage measurements in exhaust ducts as these tests require the combination of low error volume flow measurements in ducts, CFD analysis as well as data modelling to produce plausible results.

Following the different phases of the commissioning of the ventilation system, the applied measurement concepts and strategies, results and lessons learned within the multidisciplinary field of fluid dynamic, thermodynamic and process control validation testing are discussed.

Keywords: ventilation design, commissioning, measurement approach, volume flow measurement in ducts, leakage measurement

1. INTRODUCTION

The Gotthard Base Tunnel (GBT) is the longest railway tunnel in the world and is soon to be opened (June 2016). Before opening the general operation approval has to be given by the FOT (Federal Office of Transport). Part of the approval process are the tests involving all the components and interfaces of the ventilation system.

The commissioning and testing of the ventilation system consists of several phases. The following phases are discussed in this paper:

- Commissioning stages such as
  - Factory acceptance tests before installation
  - Initial start-up of the ventilation system
  - Combined functional tests

- Measurement and validation of climate and ventilation goals

The goal of this paper is to give an overview of measurement and proofing concepts and strategies, results and lessons learned within the broad field of commissioning and testing this system. An especially challenging and innovative concept of the leakage measurements in exhaust ducts during the first start-up of the Faido ventilation station is presented in detail in the case study below.
THE GBT VENTILATION SYSTEM

The ventilation system of the GBT consists mainly of the following parts:

- Underground ventilation central Sedrun with two fresh air fans (1.5 MW each) and two exhaust fans (2.4 MW each). Each axial fan has a diameter of 2.8 m. Every fan’s speed blade angle is controllable
- Aboveground ventilation central Faido (analog to the station in Sedrun)
- 28 smoke extraction vents with ventilation dampers (4.3 x 5 m)
- 12 jet fans at the portal Erstfeld and 12 jet fans at the portal Bodio
- An array of sensors in the tunnel tubes and in the emergency stations

COMMISSIONING STAGES OF THE GOTTHARD BASE TUNNEL VENTILATION SYSTEM

The commissioning and testing of the Gotthard Base Tunnel ventilation system was a challenging task especially due to the large distance between the ventilation stations and the other components of the ventilation system. The ventilation station Faido is located above ground and connected to the tunnel with a 2.7 km long access gallery, sucking and blowing air through dampers located near the tunnel itself. The Sedrun ventilation station is located in an underground cavern, connected by two 800 m deep vertical shafts to the tunnel. The jet fans, also part of the ventilation system, are located at the portals of the tunnel. In total the different components and stations spread over the entirety of the 56 km tunnel, and are connected over hundreds of kilometers of cables.

Furthermore, during all the ventilation tests, construction and commissioning work was carried out throughout the tunnel. To provide sufficient ventilation and cooling of the construction site, the temporary ventilation system was still active and had to be deactivated for the test phases of the permanent ventilation. When testing operation points of the fans all air ways blocked by the temporary ventilation system and extra leakages had to be accounted for.

Several electromechanical components are not functionally associated with the ventilation system, but are essential to the functioning of the ventilation system. For example, the doors to the emergency stations serve as air dampers for the ventilation of both station and tunnel. The doors and gates, the elevator in the vertical shaft in Sedrun, the HVAC ventilation systems of the underground facilities and the cross sections and the energy supply system have their own master controller which communicates via cross-connections with the master controller of the ventilation system. These systems have to be controlled remotely by the ventilation system master or at least monitored to ensure the proper functioning of the ventilation as a whole.

The above mentioned challenges made the commissioning and validation testing especially demanding and thematically broad. The general approach to testing and validation of technical components and systems, or better the measurement of the underlying physical processes, is a feedback loop. It starts with the modelling of the system and the establishment of the measurement goals. Once these have been sought out, different measurement concepts are weighed up against each other. The heaviest weighting in commercial testing is typically placed on feasibility, cost and expected measurement error. Especially cost and achievable measurement precision are somewhat in stark contrast.
After the measurement concept has been established, sensors and data acquisition units are put in place and the data can be sampled. Most of the time, then, since the sought after quantity cannot be measured directly, the data has to be analyzed, filtered and fit to a previously derived model. Fitting a model to the data is especially useful for extrapolation to other conditions or operating points, which could not be tested.

With the best fit model at hand the feedback loop closes with the formulation of conclusions and/or requirements for the tested systems. This approach was implemented for every testing and validation task of the GBT ventilation system.

### 3.1. First test phase: Initial start-up of the ventilation stations and stand-alone tests

Before installation, most of the components had to undergo factory acceptance tests. The interaction between the functional units was tested with emulations of the GBT ventilation control system. These emulated tests, including MMI and functional tests, served as the main platform for last optimizations to be done to the equipment. The ventilation stations with 4 fans each were initially started in January 2015. Before the initial start-up, the exhaust ducts were commissioned and integrated into the master controller, so that the airways could be opened by remote control. The emergency doors, which act as fresh air dampers, had to be opened manually during the first start-up. In this phase, the control system of each axial fan and its auxiliary systems such as external cooling and hydraulic fan blade adjustment was tested.

During the first start-up of the Faido fans precautionous high frequency pressure measurements were done to establish the exhaust duct loading. Results showed differential pressure peaks approx. 35% above stationary conditions but still below model predictions. These measurements were also used to establish whether the time between the staggered start-up of fresh air and exhaust air fans could be shortened.

At the end of this intense test phase the proper stand-alone function of all systems such as axial fans, jet fans, tunnel climate measurement and fire detection systems was proven and analysed. Feedback from the measurement campaigns, which were run in parallel, helped fine tune operational points or operating control modes of the system.

One of the most challenging test cases involved the measurement of leakage flow through the exhaust air duct boundaries along the Faido gallery during the first start-up of the Faido ventilation station. This quantity is relevant in the setting of the operating points of the fans, as it has to be added on top of the flow rate required in the emergency station, at the beginning of the duct.

### 3.1.1. System modelling and uncertainty of the leakage flow measurement

As described above, first a model has to be derived. According to [2] ducts can be treated as ventilation ducts for underground mining. In essence a porous duct in which air flows and which through static pressure differences draws (or expels) extra air mass from or to the surrounding environment. The exhaust air duct and measurement setup is shown in Figure 1.

A minimum of two mass flow measurements are necessary to calculate the leakage of the duct. As well as the flow, the differential and absolute pressure, temperature and humidity have to be sampled.
The quantity we are interested in is the leakage mass flow rate $\Delta \dot{m}$:

$$
\Delta \dot{m} = \int_{0}^{L} \rho(x) \frac{d\bar{u}}{dx} A dx = \dot{m}|_{L} - \dot{m}|_{0} = \dot{m}|_{x=2400m} - \dot{m}|_{x=50m} \tag{1}
$$

Where $\bar{u}$ denotes the local mean air flow velocity in the duct, $L$ is the duct length, $A$ is the cross section area of the duct, assumed to stay constant in this formula. $\dot{m}$ represents the mass flow rate. When measuring this quantity at least 2 synchronous measurements $k$ are necessary at the ends of the duct (see Figure 1). Hence the measurement uncertainty of the leakage $\Delta \dot{m}$ becomes:

$$
\partial \Delta \dot{m} = \sqrt{\sum_{i}^{n} \left( \frac{\partial \dot{m}}{\partial a_i} \Delta a_i \right)^2} = \sqrt{2} \star \partial \Delta \dot{m}|_{k} \tag{2}
$$

Where $a_i$ denotes an independent variable for the computation of $\dot{m}$ and $\partial \Delta \dot{m}|_{k}$ is the uncertainty of the measurement in one of the 2 cross sections.

Unsurprisingly, the uncertainty of the measurement is a strong function of $\Delta u$, our ability to measure the mean velocity as certain as possible. Of course, $\partial \Delta \dot{m}$ also depends on variables such as absolute pressure, temperature and the area of the duct, all of which have a smaller influence on $\partial \Delta \dot{m}$.

From the equations which govern $\partial \Delta \dot{m}$ we notice the following statements (see also [2]):

- $\partial \Delta \dot{m}$ grows with higher $\bar{u}_k$
- $\partial \Delta \dot{m}/\Delta \dot{m}$ should be as low as possible

The above statements lead us to make measurements of $\Delta \dot{m}$ with $\bar{u}_k$ as small as possible and $\Delta \dot{m}$ as high as possible. $\Delta \dot{m}$ grows with increasing distance $L$ between the measurement cross sections and increasing differential pressure from the duct to its environment. $\bar{u}_k$ is as small as possible when the only flow flowing in the duct is $\Delta \dot{m}$ itself, achievable, in our case, when the fans draw air against closed exhaust dampers in the emergency station.

To be able to parametrize the duct to later be able to extrapolate to different operating points we need to model the left hand side of equation (1). According to [2], 2 models can describe the flow through porous ducts:

$$
\frac{du}{dx} = \frac{U}{A} f_{turb} \sqrt{\frac{2\Delta p}{\rho}} \tag{3}
$$

Or:
The turbulent model (3) assumes that with growing $\Delta p$ (mean differential pressure between $0$ and $L$) the increment in leakage decreases (square root function). The laminar model (4), also known as the Darcy law, predicts a proportional increase of leakage with growing $\Delta p$ (linear function). The derivation of these models can be found in [2].

By measuring the differential pressure between the duct and its environment, we are able to fit parameters to the data, and use these to track leakage over operating time or establish massflow rates in conditions which might occur in the future.

Having established what we would like to measure and what the consequences of uncertain measurements are, we proceed to defining the measurement strategy and tools.

### 3.1.2. Measurement strategy and CFD-Analysis

Referring to Figure 1 and equations (1) through (4) we need to measure the following quantities:

- Volume flow $\dot{Q}_k = \bar{u}_k A_k$ [m$^3$/s]
- Temperature $T_k$ [K]
- Absolute pressure $p_{abs,k}$ [Pa]
- Differential pressure $\Delta p_k$ [Pa]

A large variety of methods exist to measure $\dot{Q}_k$ ([1],[2],[3]). Table 1 weighs the pros and cons of the most popular measurement strategies.

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
</table>
| Equal area methods, Log Chebychev Grid [3] | Measurement grid with a minimum of 20 sensors in the cross section of interest. Sub-area weighted integral to find average $\dot{Q}_k$ flowing through $A_k$. | • Low measurement error  
• Standard, well known technique for precise measurement of confined volume flow | • Time consuming setup  
• Costly measurement equipment (20 Sensors!)  
• Duct blockage  
• Tends to overestimate the volume flow |
| Tracer Gas measurements [3]    | Measure the concentration of a tracer gas from source to measurement         | • No knowledge of geometry of duct needed  
• Independence of flow velocity profile                             | • Costly, non-portable measurement equipment  
• Not environmentally friendly  
• Homogeneous mixing required  
• Only few suppliers |
| Ultra Sound Measurements       | Measurement of average $\bar{u}_k$ over measurement path via ultra sound emitter and receiver | • Direct measurement of average $u_k$ along sound wave path  
• Very precise measurement devices readily available on the market  
• Standard and reliable measurement for normal operation in Tunnels | • Costly, usually non-portable, sensitive measurement equipment  
• Several measurement paths needed for non-standard geometry measurement of $\dot{Q}_k$  
• Time consuming setup |
### Table 1: Method Description, Pros, and Cons

<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single point measurements</td>
<td>Measurement of $\bar{u}_k$ with previous hypothesis of velocity profile.</td>
<td>- Very Cost effective measurement (only 1 Sensor)</td>
<td>- Previous knowledge of velocity profile is imperative for calculation of $Q_k$</td>
</tr>
</tbody>
</table>

Feasibility, cost and measurement uncertainty are therefore the main decision factors for which strategy to go for. As the geometry and resistance coefficients of the duct were well known beforehand and do not change within our measurement path $L$ we opted for a single point measurement in combination with CFD-Analysis. This strategy is cost and time efficient.

The scopes of the CFD-Analysis includes:

- Compute stationary velocity profiles in the duct for different volume flows
- Establish the measurement location to minimize the error of the measurement of $u_k$

The results of the CFD-Analysis should give a factor $B_{CFD} = f(u_k)$ such that:

$$\dot{Q}_k = A_k \cdot \bar{u}_k = B_{CFD}(u_k) \cdot u_k$$

(5)

$u_k$ here denotes the measured local velocity and $\bar{u}_k$ is the mean flow velocity in the measurement cross section. The mean flow velocity $\bar{u}_k \sim u_k$ influences the velocity profile shape. Therefore $B_{CFD}$ is a function of $u_k$.

Using the CFD results the optimal measurement location can be chosen to be at the height $z$, distance from the centre of the profile $y$, so that the profile at this height $z$ is as flat as possible for as wide of a range of $z$ as possible. Mathematically:

$$\min_{y,z} \frac{\partial u_k}{\partial y}$$

(6)

For fully developed flow this is mostly at the point where $u_k = \max(u_k)$. In this way, the systematic error of positioning the probe can be reduced to a minimum as the profile is presumed to be as flat as possible.

#### 3.1.3. Data analysis and results

The measurement setup is the result from sections 3.1.1 and 3.1.2. They can be seen in Figure 1. The two single-point measurements ($u_k$) were placed at $x = 50$ m and $x = 2400$ m from the fans in the centre of the duct ($y = 0$ m) and at a height $z = 1.05$ m above the false ceiling.

The fans were operated at 12 different points. Once stationary conditions were reached at least 4 minutes worth of data was sampled. Computing $\Delta \dot{m}$ from the raw data with equation (1) and applying the derived models (3,4) we can approximate the leakage massflow. The laminar model (3) is conservative at high $\Delta p_{mean}$ in the duct (linear increase of leakage with $\Delta p_{mean}$). The turbulent leakage model (4), is conservative at low $\Delta p_k$ in the duct. A mixed model was therefore assumed, which sums the laminar and turbulent leakages to give total leakage. This model lies between laminar and turbulent leakage, accounting for changes in flow turbulence with changing $\Delta p_{mean} \cdot f_{turb}$ in our case resulted to be $1.922 \left[ \frac{mm^2}{m^2} \right]$ and $f_{lam}$ is in the order of $3.197 \times 10^{-12} \left[ m \right]$, which according to [2] is a very sealed duct. Figure 2 illustrates the obtained results.
The fitted model can now be used to calculate leakage for conditions that were not directly measured. Also, quantitative conclusions can be made by comparing the tested object to others. The feedback loop closes with the fine tuning of operating points of the fans. After this phase, the stand-alone components had to be integrated into the tunnel control system.

3.2. Second commissioning phase: Combined tests including the train control system and auxiliary electromechanical systems

From August to September 2015, the ventilation system was tested for the first time as a complete system. Before these tests could start, relevant electromechanical systems master controllers such as the train control system, emergency doors, the HVAC of technical rooms, doors and gates were integrated into the tunnel control system and their cross connections to the ventilation master controller were set up and commissioned. Several major test cases proved the proper automated response of the ventilation system to an incident detection of the train control system e.g. in case of fire on a train. Immediate smoke extraction in the predicted tunnel emergency station and fresh air supply to the escape ways is needed in that case.

During the planning of the system 44 ventilation strategies were defined for every conceivable scenario. Each strategy includes a control scheme for the ventilation and its surrounding systems. Most ventilation strategies include the two ventilation stations. When a ventilation strategy is initialized, the ventilation ducts are prepared and all dampers, doors and gates are brought into the necessary positions in several consecutive steps. These actions are performed and supervised by the dedicated redundant master controller. Local functions such as start or redundancy switches were previously successfully tested during the initial start-up phase.

In the end of the combined commissioning phase, every single ventilation strategy had been activated and all volume flows of the axial fans, in the airways and in the tunnel as well as

---

Figure 2: Comparison of leakage flow models. Relative deviation [%] of predicted to measured leakage flow [kg/s] as a function of mean differential pressure in the duct.
pressure differences between the tunnel tubes were measured. The measurement of these previously defined reference values were used to validate computational models used in the dimensioning of the system and iteratively tune operating points. For example, exhaust dampers were adjusted to achieve a homogenous exhaust flow through all 7 exhaust vents of each emergency station. Previous CFD analysis established the damper blade opening angles which were then hard coded into the control of the dampers. Volume flow measurements allowed the validation of the made assumptions.

Immediately after the combined tests, the test operation of the tunnel including electric driven rail tests with a maximum velocity of 275 km/h started. During this test phase from October 2015 until May 2016, a total of 37 tests with realistic operation conditions and train traffic, smoke and heat generators were done to verify the validation for operation approval by the FOT.

4. CONCLUSION

In this publication commissioning and testing methods applied to the Gotthard Base Tunnel are discussed. The general structure of its ventilation system, the interfaces and different components are outlined. Especially the large distances between components of the system and ongoing construction work from third party lots during commissioning work proved to be challenging.

Following a case study of one of the many tests performed during the 3 year commissioning period the general methodology of testing is explained. A comparison between several methods of measuring volume flow in ducts is given. Drawing on this comparison, a new method is introduced, which is based on the combination CFD analysis and single-point measurements. The relative uncertainty in the outlined leakage measurement varies between 15% and 20% for the very sealed duct which was tested (small leakage flow). Furthermore, a mix of turbulent and laminar leakage flow models is used to predict this flow within a margin of 10% in the relevant operating points.

The commissioning and testing phase of the complex GBT ventilation system required an early and accurate planning and coordination. Time slots for the tests had to be reserved with a special focus on the contractual situation of all other contractors of the tunnel.

Volume flow in all emergency stations and open doors, smoke propagation and the recirculation on the portals were measured to provide proof of defined targets and ensure the safety of future train passengers as well as operators of the tunnel.

5. ACKNOWLEDGEMENTS

The authors would like to thank the AlpTransit Gotthard Ltd for kindly authorising to publish of the content of this paper.

6. REFERENCES

[1] Strömungs- und Durchflussmesstechnik, O. Fiedler, Oldenbourg, 1992