Numerical simulation of the Mont Blanc Tunnel ventilation system

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HPC Enabling of OpenFOAM® for Industrial Applications
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Outline

Where it all began...

Collaboration started in 2009, among:

- Department of Engineering Enzo Ferrari **(DIEF)**, University of Modena and Reggio Emilia
- Gruppo Europeo di Interesse Economico del Traforo del Monte Bianco **(GEIE-TMB)**
- **mimesis** s.r.l., a spin-off of DIEF

on the **study and optimization of the Mont Blanc tunnel ventilation system**.

Project objectives:

- to collect extensive **physical data** and information on the airflow in the tunnel
- to develop **predictive tools** for the study of ventilation configurations and/or critical scenarios
- to propose new **control strategies** to reduce the response times in case of event

Methodologies:

- The research is carried out by both **modeling** and **experiments**, combined in an integrated approach for analysis of this class of problems
- Experiments provided accurate **in situ air velocity data** for model development and validation, and the verification of airflow control infrastructures

The TMB and its ventilation system I

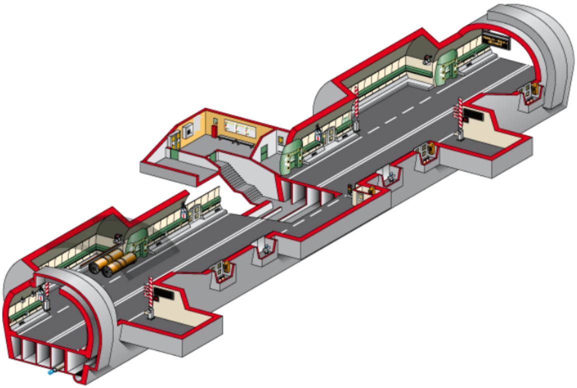
The **Mont Blanc Tunnel**:

Two-way road tunnel connecting Italy and France, **11611 meters** long with three different slopes

The tunnel is equipped with a **hybrid semi-transverse** ventilation system, including:

- A **fresh air supply** system, with 1160 vents along the Italy-France sidewalk
- A **smoke extraction system**, with 116 openings on the tunnel vault
- A longitudinal flow control system, with 38 **jet fan** couples mounted on the tunnel ceiling
- A **pressurization** system for the stashes (recovery in event of fire)
- A number of **sensors** (anemometers, barometers, thermometers, pollutants detectors, differential pressure sensors)

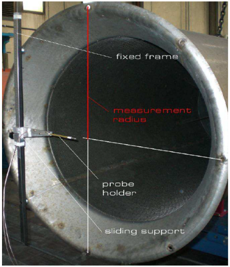
The TMB and its ventilation system II



Tunnel schematic

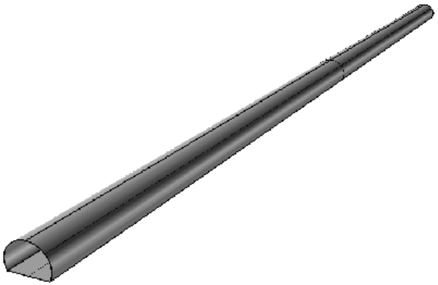
Experimental work

- **In vivo** experimental campaigns
  - **Fixed-point** measurements
  - **Continuous** profile acquisitions (T.A.L.P.A.)
- **Jet fan** characterization
  - static profiles
  - hot wire anemometry
  - measurement of u_z, u_r, u_θ, k



Objectives of the numerical work

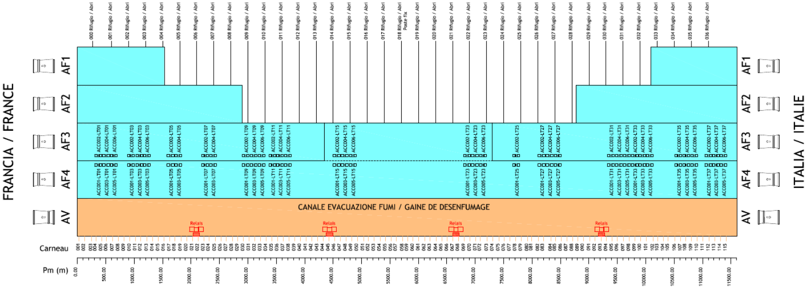
- Development of a **1D simplified network model** to simulate the global behaviour of the ventilation system
- Development of a **complete CFD model of the whole tunnel**
  - ... to enable detailed flow analyses on a global scale
  - ... to demonstrate the feasibility of CFD for such a large and multi-scale domain
  - ... to provide the basis for future studies of real scenarios (air quality control with heavy traffic loads, fire events, etc...)



Outline

Critical aspects

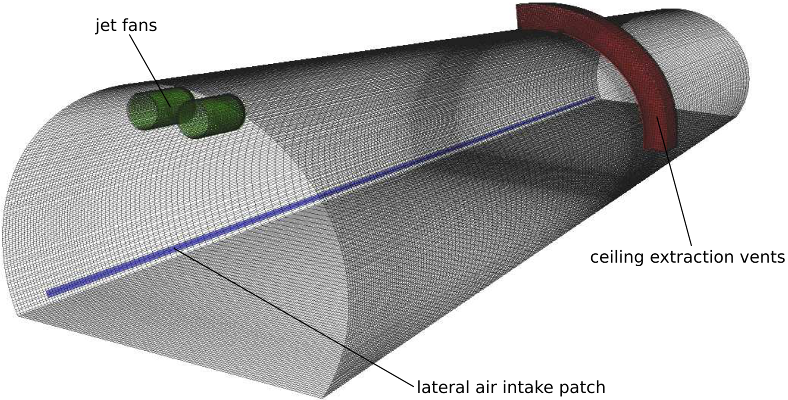
- **Huge domain**: an evident computational challenge
- **Ventilation elements**: jet fans, fresh air vents, smoke extraction outlets imply the presence of jets and shear layers of different scales and orientations
- **Complex modularity**: the automation of the geometrical modeling and discretization phase is hindered by the non-trivial layout of the different ventilation elements (see below)
- Presence of **small scale geometrical details** such as sidewalks, niches, lighting, panels, sensors, etc. which have an influence on the flow



Modeling choices I

- **Turbulence**: the scale of the problem makes resolved turbulent simulations like LES unfeasible. Turbulence is accounted for by means of the **realizable $k - \varepsilon$** RANS model
- **Geometrical simplifications**: small scale details are not included in the models, and are substituted by an **equivalent wall roughness**
- **Jet fan modeling**: jet fans are modeled as hollow cylinders with **ad-hoc BCs** (`swak4Foam`) at the intake and discharge sections
- **Lateral air supply vents**: the accurate modeling and meshing of the small air supply vents is regarded as a computational overkill. The vents have been substituted by **continuous boundary patches** in the computational model
- All physical **equivalences** have been **suitably tuned** thanks to the extensive experimental database

Modeling choices II



Wall roughness

The friction factor f is extracted from experimental data using the Darcy-Weisbach equation:

$$\Delta p = f \frac{L}{D_h} \frac{\rho U^2}{2}$$

The average surface roughness ε is calculated via the Colebrook equation:

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(\frac{\varepsilon}{3.7 D_h} + \frac{2.51}{Re \sqrt{f}} \right)$$

The logarithmic law of the wall for hydraulically rough flows is then enforced:

$$u(y) = \frac{u_\tau}{\kappa} \ln \frac{y}{y_0} \qquad y_0 = \frac{\varepsilon}{30}$$

Jet fan ad hoc BCs

At the **fan suction inlet** (an outlet for the CFD model):

- pressure is imposed as equal to the average pressure at the discharge section, minus the nominal pressure jump given by the fan;
- a zero gradient condition is imposed for velocity components.

$$p_s = \bar{p}_d - \Delta p_{fan} \qquad \frac{\partial \mathbf{u}}{\partial n} = 0 \tag{1}$$

At the **fan discharge** (an inlet for the CFD model):

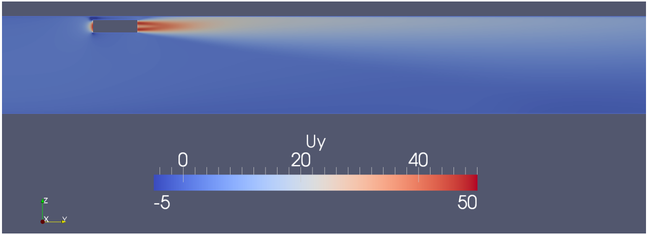
- velocity is imposed as equal to the average velocity at the suction, multiplied by the reconstructed dimensionless velocity profile (ensuring mass conservation);
- a zero gradient condition is imposed on pressure.

$$\mathbf{u}_d = \bar{U}_s \tilde{\mathbf{u}}_\mathbf{d} \qquad \frac{\partial p}{\partial n} = 0 \tag{2}$$

Validation runs I

Simulations with 1,2 and 3 **active jet fans couple** across a 900 m long segment of the tunnel compared with experimental data in order to **test physical equivalences**

- **isothermal** and **steady-state**
- **unidirectional** flow field
- upstream and downstream **distributed pressure losses** taken into account at domain's end (with **swak4Foam**)
- **second order** spatial discretisation schemes

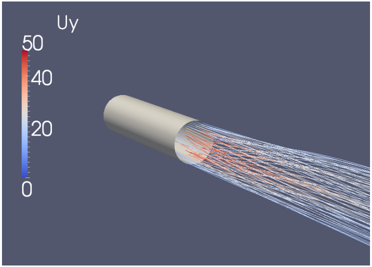


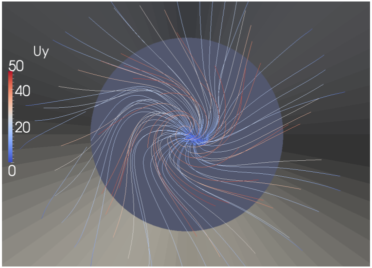
Validation runs II

Good agreement in terms of longitudinal mean velocity

N. of active fan couples	1	2	3
U_{exp} [m/s]	3.10 ± 0.20	3.21 ± 0.20	3.17 ± 0.20
U_{num} [m/s]	3.209	3.387	3.399

Reliable simulation of **swirl component** in fan discharge section





Outline

Toolchain

The work has been carried out entirely with **open source** software:

- **OpenFOAM®**: pre-processing and solving phases
- **PyFoam**: exploited to chain the scripts used throughout.
- **swak4foam**: fast and easy implementation of customized BCs
- **ParaView**: post-processing

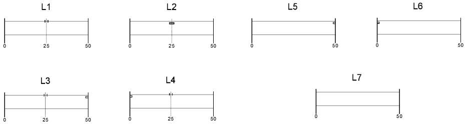
Toolchain:

- `gnu/4.5.2`
- `python/2.7`
- `openfoam/2.1.1-gnu-4.7.2`
- `pyfoam/0.5.7`
- `swak4foam0.2.1`
- `ParaView/3.14`

Modular approach

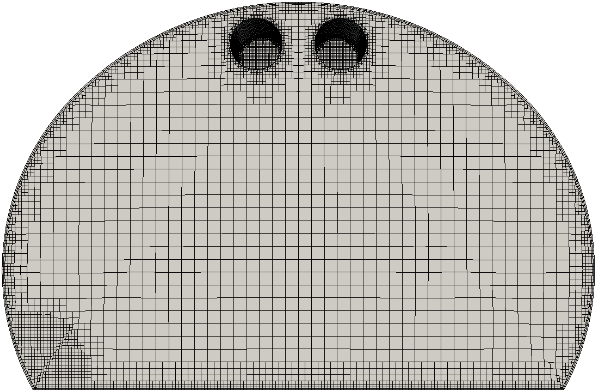
- Exploitation of **layout patterns** repetition in the tunnel
- Seven **elemental blocks**, each 50 m long, have been singled out, which, if appropriately **concatenated**, could virtually represent the physical domain in its entirety*
- Meshing has been performed **independently** on each of the seven blocks using `snappyHexMesh`

***with some approximations**

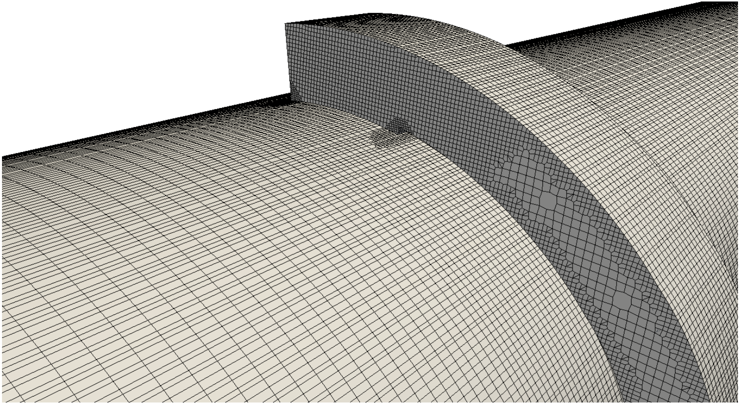


Block type	Quantity	MCells
L1	84	0.64
L2	6	1.11
L3	6	1.07
L4	26	1.07
L5	26	0.87
L6	6	0.87
L7	78	0.20
total	232	138

Meshing I



Meshing II



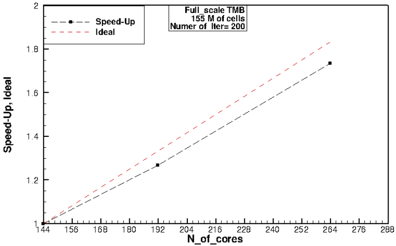
Assembly of the whole model

- **Python/PyFoam** scripts
- `mergeMeshes` utility (serial process)
- Arbitrary Mesh Interface **(AMI)** to connect faces of consecutive blocks
- Different **slopes** taken into account
- **Boundary conditions** assignment
- The procedure is general and absolutely **portable**

- Final model assembly @ CINECA
  - **138 M** of cells
  - Usage of **91 GB** of RAM: a **“fat node”** was used
  - **3 hours** of wall-time

Scalability

- Runs have been done on the compute nodes of the **PLX cluster** (2 hex-core Intel Xeon 2.40 GHz)
- `buoyantBoussinesqSimpleFoam`
- Three runs have been done using 12, 16 and 22 nodes, that correspond to **144**, **192** and **264** cores



n. of nodes	n. of cores	cells per processor	n. of it	WCT	Cpu-hours
12	144	0.9 M	210	50812 s = 14.11 h	2032
16	192	0.7 M	210	39906 s = 11.09 h	2128
22	264	0.5 M	210	29126 s = 8.09 h	2135

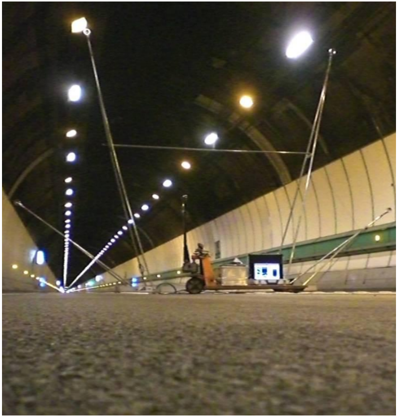
Reconstruction and post-processing

- The variable fields have been saved every 50 iterations, and they have been reconstructed using the `reconstructPar` utility.
- Memory demanding operation. Example: with Np=**144 procs**, **110 GB** of memory used, **11 hours** of cpu-time, and **13 GB** of data occupancy for each time-field.
- Remote Visualization using ParaView on **CINECA** servers. It is mandatory, at least, to employ a node with 128 GB of memory or bigger.
- Loading time for the entire model is around 30 min. Simple **manipulation operations** can easily be performed.

Outline

TestCase number 1

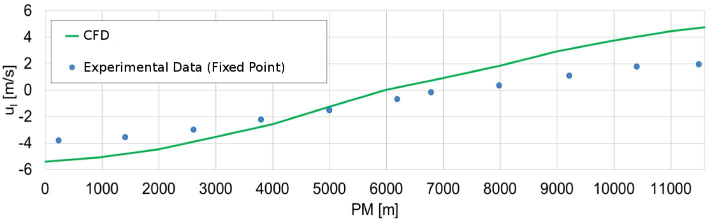
- Based on **fixed point** measurements
- **Ventilation system** configuration:
  - Lateral air intake - **ON**
  - Exhaust air extraction - **OFF**
  - No. active *jet fans* - **NONE**
- Run on 192 cores @ CINECA
- 800 iterations



Results

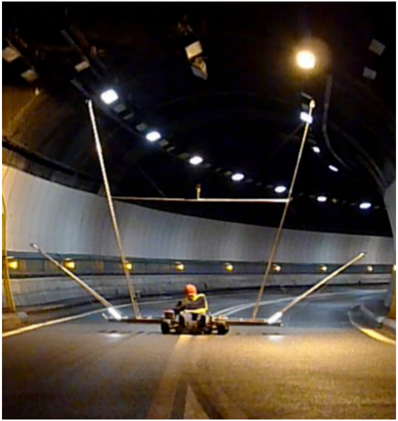
Average longitudinal velocity: **acceptable results**

- **Convergence** not reached
- Uncertainty on **measurements** that reflects on BC
  - Lateral **mass flow rate**
  - **Δp** between portals



TestCase number 2

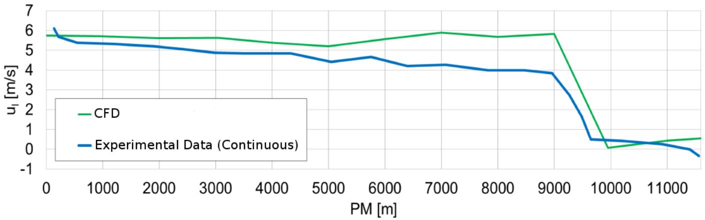
- Based on **continuous** measurements
- **Ventilation system** configuration:
  - Lateral air intake - **OFF**
  - Exhaust air extraction - **ON**
    from PM 9000 to PM 9600
  - No. active *jet fans* - **4**
    2: Italy→France
    2: France→Italy
- Run on 264 cores @ CINECA
- 700 iterations



Results

Average longitudinal velocity: **acceptable results**

- **Convergence** not reached
- Uncertainty on **experimental data**
  - Strange **loss** of velocity, probably due to **leakage** before PM 9000 along the depressurized extraction channel
  - In the simulation extraction gates are **perfectly closed**



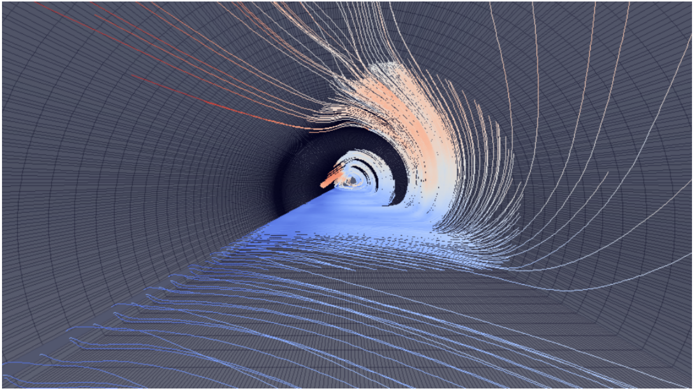
Scalability

Simulation	n. of cores	n. of it	WCT	Cpu-hours
TestCase n. 1	192	700	61570 s = 17.10 h	3284
TestCase n. 2	264	700	48213 s = 13.39 h	3536

- Scalability on 700 iterations
- From **192** to **264** processors the scalability is around 80%

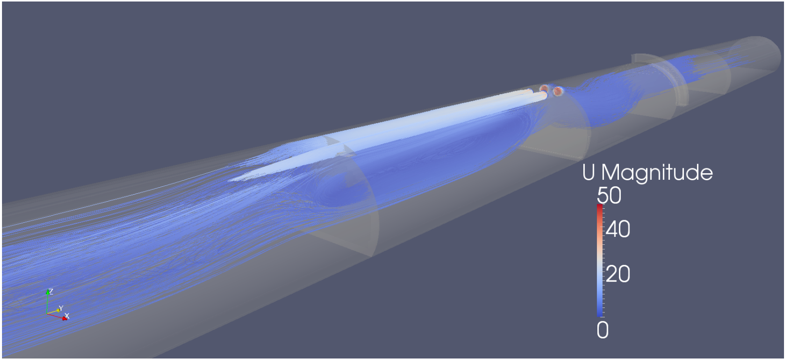
Pre-production runs: some nice pictures I

Fresh air intake (TestCase n. 1):



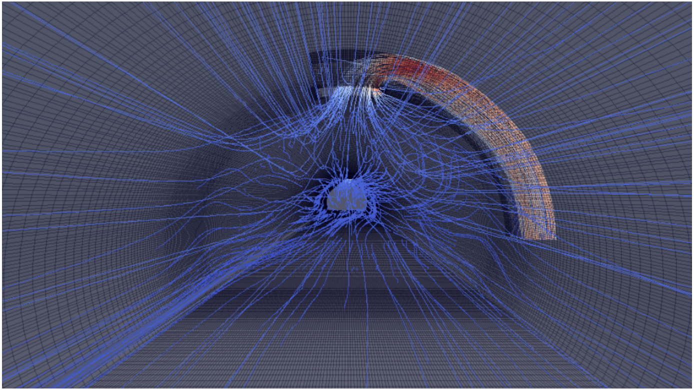
Pre-production runs: some nice pictures II

Counterflow jet fans (TestCase n. 2):



Pre-production runs: some nice pictures III

Exhaust air extraction section (TestCase n. 2):



Outline

Conclusions and further work

- “HPC enabling” of OpenFOAM®
- Satisfactory **preliminary** results

- Longer runs, more iterations for more accurate results
- Coupling modular 3D and 1D in a flexible **multi-scale simulation**

Contacts

Thanks

Thank you for your attention!

Contacts

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