# High pressure gas quenching: assessment of velocity experimental measurements and steps for model validation

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Gas quenching is a key step in the process of heat treatment of metals. To reach optimizations of the process time and quality, it is essential to correctly distribute the load inside the quenching cell. Numerical simulations using CFD (Computational Fluid Dynamics) could help us to understand the phenomena occurring into the quenching cell and identifying criteria for improving the process. However, numerical simulation must be validated versus experimental data. This paper presents the experimental and simulation works conducted in order to validate the commercial software Qobeo for the modeling of gas quenching. The computational domain has been refined, the mesh corresponds precisely to the geometries of the quenching cell and the rack. The gas flow for quenching is simulated in the atmospheric conditions for pressure and temperature. The numerical results are compared with experimental measurements of flow speed. The results obtained are very encouraging, coherent behaviours are observed in both cases. However, further improvements should be conducted for better approaching the actual quenching conditions. For modelling aspects, high pressure (up to 20 bar), high temperature (up to 900 °C) and various gases ($N_2$, $CO_2$, He) should be included. For experimental aspects, the uncertainty of gas flow measurement technique should be determined as well as improving the assessment of flow orientation.

**KEYWORDS:** GAS QUENCHING - CFD - SPEED MEASUREMENTS
GAS FLOW - HEAT TREATMENT - HPGQ

## Context

**French Institute of Technology for Material, Metallurgy and Process (IRT M2P)**

In France, 8 French Institutes of Technology (IRT) have been created in the 2010 decade. The common target of such Institutes is allowing transfer of knowledge and development between academics and industrials in specific fields. The IRT's sites are smartly distributed in French regions, close to the industrial activity sources as shown in Fig 1.

The works presented here have been conducted by the French Institute of Technology for Material, Metallurgy and Process (IRT M2P). The IRT M2P is a partnership built up in 2013 in order to accelerate innovation, allow integration of

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new technologies and to share a technologic platform of industrial scale for tests.

The Institute is located in the east of France, close to an important network of heat-treatment and materials industries. Also, universities and technical centres of excellence are in the surroundings.

This paper illustrates the mutual works conducted by IRT M2P with shared resources between industrials. It gathers contributions of: Air Liquide (gas industry), Faurecia (automotive industry), IRT M2P (supplier of the technical platform), SCC consultants (innovative company offering its knowledge in fluid simulation and computer systems), ECM furnace producer.

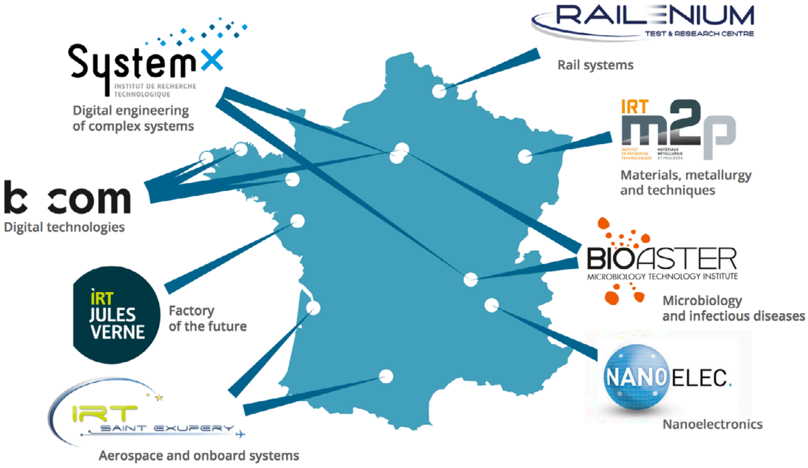


**Fig.1** - Location of French Institute of Technology. The IRT M2P is located in the east of France

## Introduction

Potentialities offered by gas quenching are huge, if the process is correctly mastered. The present work is focused on optimization of gas quenching, first experimentally and secondly by developing sustainable models able to forecast cooling rate.

## Gas quenching and oil quenching

A key project has been launched in IRT M2P to improve our knowledge in advanced heat-treatments, especially quenching (1). In industries, oil quenching is largely spread but exhibits several disadvantages: absolute necessity to wash parts after treatment, recyclability of oil after use, detergent rejection and compliancy with ecological regulations more stringent. Moreover, flexibility is weak when oil containers overcome a volume of 1 $m^3$ and temperature should be regulated precisely at different set points. The key advantages of gas quenching are: the metallic parts do not need any post washing, the homogeneity of heat treatment of the load is enhanced and the intensity of quenching can be controlled precisely, but also, the distortion of parts is dramatically reduced compared to traditional technology. Nevertheless, the parts are concentrated in a small volume into the quenching cell and the technology is not as mature as oil quenching. Large potentialities of development exists for gas quenching, this work aims to provide knowledge in this field (2).

## The gas quenching technology

During gas quenching, the parts are cooled from the treatment temperature, often approximately 900 °C, until room temperature in a given time dependent on the quenching intensity required. In this cell, the gas is injected at high pressure (20 bar max), then a turbine located on the top blows the gas towards the load. The gas is heated up when enters into contact with the hot parts. The gas is cooled down when passes throw a heat exchanger located in the wall of the cell, then directed toward the turbine again. The gas flow in the cell is shown in Fig. 2. For certain configurations of load, in particular the massive ones, an unidirectional gas flow showed to be insufficient to guarantee the uniformity of treatment. In order to address this issue, quenching cells equipped with two turbines were design, in general located on both lateral sides of the cell. Some other manufacturers design alternative flow and rotating deflector to orientate the flow in all the directions (3).

The prediction of distortion of parts submitted to heat treatment and quenching is tricky whatever the quenching media is, oil, water polymer mixture or gas. In the case of gas, such prediction requires a correct prediction of the heat transfer by convection from the solid towards the gas. The main difficulties are, in one hand, the prediction of gas circulation when the metallic parts are assembled in a rack, and on the other hand, the calculation of the actual heat exchange coefficient and the change of metallographic properties of metal when cooling. Also, in gas quenching parts hidden by obstacles could receive less gas flow, leading to a higher dispersion level for a given cooling rate. The composition of the atmosphere used for quenching has a critical influence in the final characteristics of the parts. It has been shown that an atmosphere composed of 90 %nitrogen and 10 % helium can provide a profile of temperature decrease similar to the one of oil (4). Changing the gas or the proportions of a mix, can lead to improvements of quenching performance, so conducting tests with a mixing of helium and another gases could present interesting opportunities.

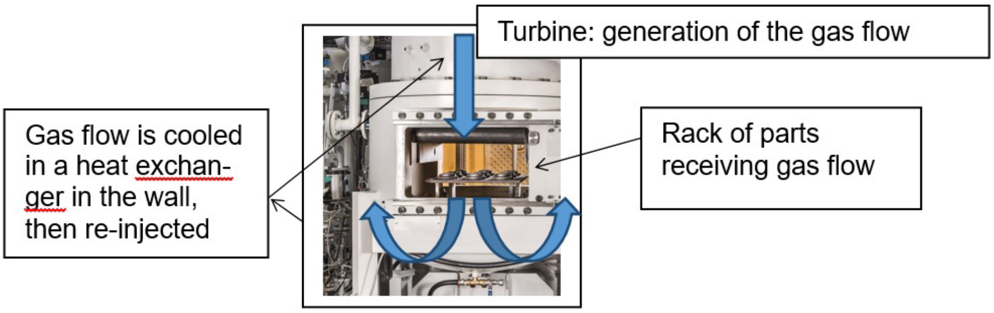


**Fig.2** -Industrial gas quenching facility, gas flow follows the direction of blue arrows

## Quenching experimental device

### Furnace and quenching cell

In this research, experimental tests of gas quenching have been conducted in the industrial furnace of IRT M2P shown in Fig. 3.
It is divided into two chambers: the first for low pressure carbo-nitriding and the second for gas quenching.
The parts for heat treatment are ranged in a rack of around 250 kg. After the high temperature stage in the cell at the back of the furnace, they are transferred automatically to the quenching cell.
The gas quenching cell is on the front, it allows also the entrance and exit of the load.
The pressure of gas for quenching is set to 20 bar, which is the maximum pressure admissible for the chamber.
The higher pressure, the faster quenching; the heat exchange capacity is optimum.
The gas is sprayed from top to the bottom of the parts rack (as presented in Fig. 2).

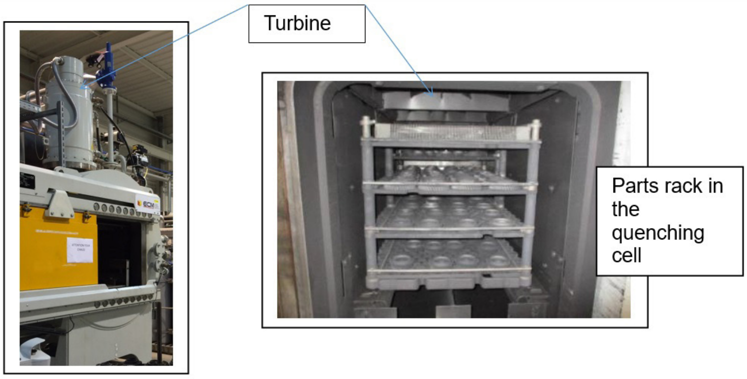


**Fig.3** - Furnace on which test have been conducted and rack of parts

**Gas flow measurements**

Experiments have been launched to get references to validate the gas flow simulation. The first trials (2) have been carried out to know qualitatively the gas flow circulation and assess visually the turbulence level. The furnace parameters are set at ambient pressure and temperature.

Observations have been set by a transparent Plexiglas plate in place of the door, allowing to track smoke circulation. A high speed camera ensures the shooting of the smoke transfer. Particular pictures are extracted from the film for expertize, see Fig. 4.

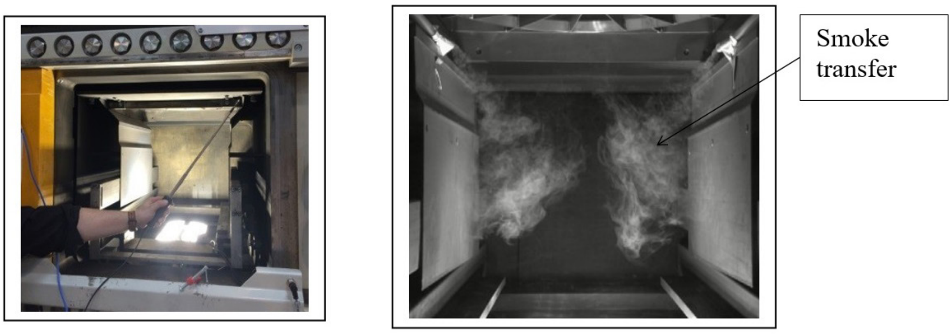


**Fig.4** - Left, quenching cell and installation for high speed camera. Right, smoke flow visualization

Fig. 5 shows honeycomb grid. On the left hand side, the real grid indicating the position of the gas flow meters that have been positioned. On the right had side, the simulation's honeycomb grid.

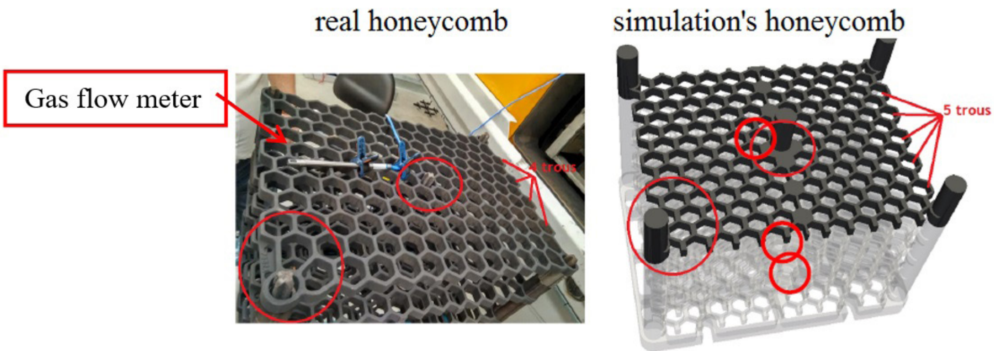


**Fig.5** - Left, real honeycomb grid with the position of gas flow meters. Right, simulated honeycomb

## Gas quenching simulation

### Quenching simulation tool qobeo®

The numerical simulation of the gas quenching has been conducted with qobeo® which is a commercial software of 3D simulation for furnaces and installations for industrial quenching. This software has been developed by the reseach consortium ThosT gathering heat treatment industries, the Center of Forming of Materials (Cemef of MinesParisTech, France) and the company SCC which is responsible for the integration and commercial activities (5,7).

qobeo® is a software design to be easily used by practitioners of heat treatment. For being used, it does not require deep knowledge in heat transfer, fluid mechanics or computational matematics. Pre-set scenarios help the user to build up his own simulation.

The mesh is build up with tetraedric elements (8), for gas phase simulation the immersed boundary technique is used and for solid phase calculation, the method of finite elements is used. It allows solving a single equations system with thermo physical properties adapted to the sub-domain (solid or fluid). qobeo® solves equations in transitory state in three dimensions for Newtonian fluids, as described here after.

Fluid mechanics:

- Resolution of the coupling speed-pressure using the non compressible Navier-Stokes equations.
- For high pressure gases, the compressibility is taken into account by the estate law.
- Modelling of turbulence with k-epsilon or other models.

Heat transfer:

- Solving of heat transfer equation.
- Modelling of radiative phenomena.
- For liquids, calculation of boiling effects.

Calculation of mechanics-metallographic effects:

- Possibility of coupling results from qobeo® with FORGE® NxT (or other software).
- An internal calculation model of the mechanics-metallographic effects is ongoing in the frame of the INFINITY industrial chair (9).

Regarding the complexity of modelling, in this work, a systematic validation of the numerical results with regards to corresponding experiments is conducted.

### Simulation domain setup

The simulation domain and geometry used in CFD modeling is presented in the Fig. 6, left. The flow is injected into the quenching cell, then blown with a turbine. The associated flow rate is 4 $m^3/s$, as given by the furnace manufacturer. This flow rate corresponds to a flow velocity of 18-20 m/s. Due to the geometrical shape of the turbine the injected flow has an axial and azimuthal components.

In the current simulations, a full 3D approach was chosen. A tetrahedral mesh of 12 million cells was chosen for the simulations, as shown in Fig. 6, right. The mesh was refined in the zone of the turbine, the flow deflector and on the honeycomb grids.

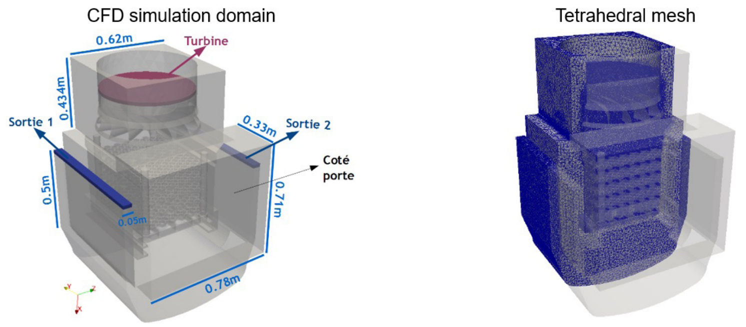


**Fig.6** - Left, CFD simulation domain. Right, mesh description

In Fig 6 left, the outlet boundary conditions are shown in blue. These are open boundaries allowing the flow to leave the computational domain, it avoids any recirculation close to the outlet. This velocity is computed and in the current simulation it is approximately 150 m/s at the outlet of the turbine. The extra space in the cell close to the door is also included into the simulation domain. Its presence has a strong impact on the flow due to the symmetry breaking in the Y direction (rear-front of the cell).

The Fig. 5 shows the grid in which the metallic parts are located. The load submitted to quenching consists of 4 plateaus of honeycomb shape. There is a small difference between the real geometry (on the left) and the modelled one (on the right): there are 4 holes for real geometry, whereas in simulations 5 holes were imposed. We assume that this difference does not induce critical error in the simulation results.

An unsteady approach is used. Due to very small time step the simulations took 3 weeks using 16 processors.

## CFD simulation results

Fig. 7 shows the main flow trajectories. The gas injected via the turbine circulates inside the cell, passes through the honeycomb grid and goes out of the computational domain through lateral outlets.
There are recirculation regions on the left and right of the honeycomb grid. In industrial situations, this region corresponds to the position of the metallic load which is quenched.
Here, the recirculation points creates enhanced turbulence zone that could help to cool down even faster the surrounding pieces.
The presence of this recirculation is also found experimentally, see Fig. 4 (right frame). In the experiments, the smoke accumulates in the recirculation region predicted by simulations.
This qualitative comparison demonstrates that qobeo® correctly reproduces the physics of the flow inside the cell.

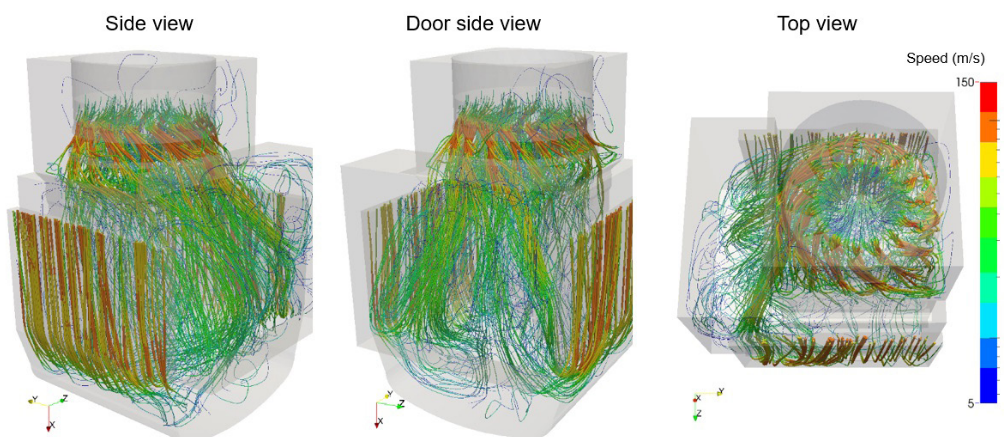


**Fig.7** - Flow trajectory

Fig. 8 shows the average velocity field inside the cell. The flow passes the turbine located at the top of the cell and passes through the grid before being evacuated throughout the lateral outlets. The presence of the honeycomb grid creates multiple recirculation points. The red arrows indicate the resulting flow speed in the positive direction of X axis, mainly top to down flow. The blue arrows evidence flow in the opposite direction. Fig. 8 shows clearly that the numerical obstacles disturbs the gas flow field, as evidenced experimentally.

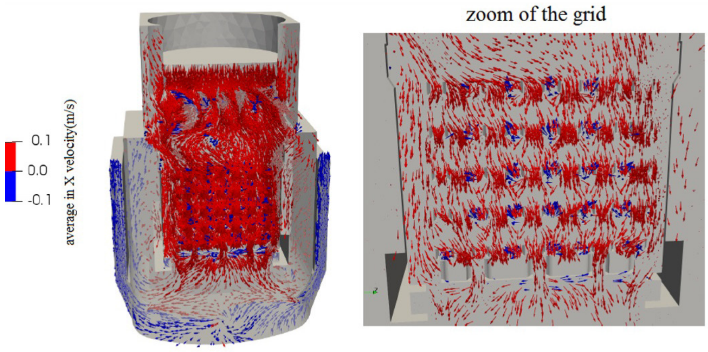


**Fig.8** - Flow field. Red arrow top towards bottom flow. Blue arrow, inverse flow

Fig. 9 presents the magnitude of the average velocity at the four levels of the honeycomb grid. At the top, on level 4, the velocity is higher than the ones observed in lower levels. The flow is inhomogeneous in the horizontal slice, this is due to the vorticity induced by the deflector. After passing through level 3 and 2 of the grid, the velocity distributions becomes more and more homogeneous and the flow tend to be laminar. The velocity is homogeneously distributed at level 1, but the speed has been divided by a factor of 10 with regards to the one of level 4. The difference observed in terms of speed and flow homogeneity between levels 4 and 1 could have a critical influence with regards to the quenching intensity of the metallic parts located in both grids. Assessing the effect of such flow difference on the final mechanical properties of the metallic parts should be done in future works.

Analysing the global computational domain, the results of Fig. 9 and Fig. 8 show clearly that the flow is not symmetric in the volume of the quenching cell. Also, the velocities become more homogeneous on the door side and closer to the bottom of the cell (near to level 1).

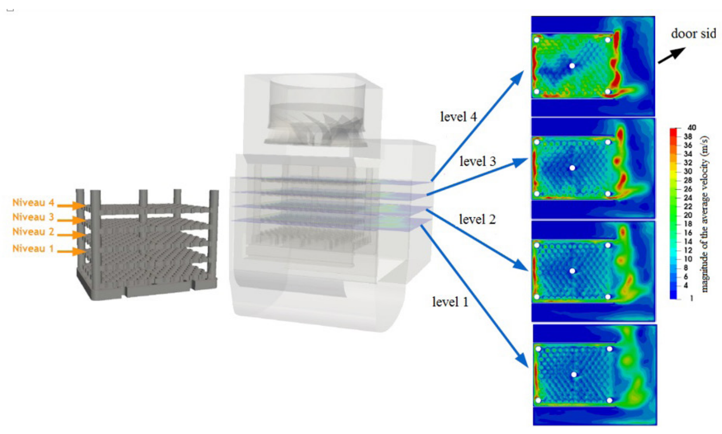


**Fig.9** - Magnitude of the average velocity at the four honeycomb grid levels

Experimental measurement (as presented in Fig. 5) and numerical measurement points were located on level 4 with 17 measurement points and in levels 3, 2 and 1 with 4 measurement points per level. The positioning of such detectors is detailed in Fig. 10. For the comparison of data from experiments and simulations, the following procedure was followed:

1. Calculation of the average velocity fields in the time interval from 15 s to 25 s.
2. Computation of the average speeds in a volume encompassing the measuring point. The volume corresponds to a cylinder of 2 cm diameter and 2 cm length (see Fig. 10, right).

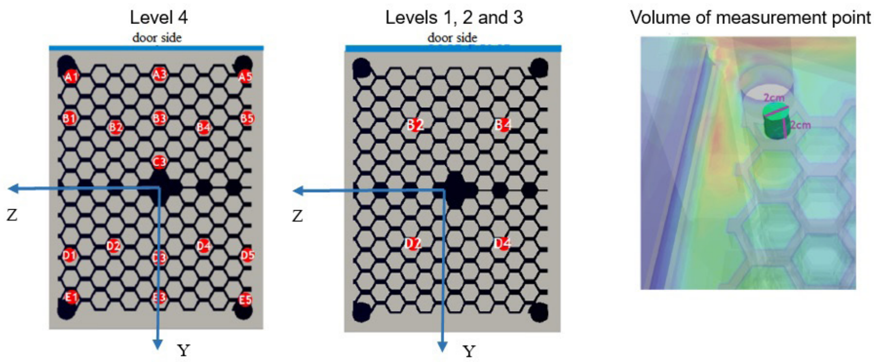


**Fig.10** - Left and centre, position of instrumentation for the measurements of flow speed. Right, measurement point

Fig. 11 and 12 present the comparison of simulation results (continuous lines) and experimental measurements (dots) at different levels of the honeycomb grid. Simulated velocities are of the same order of magnitude as the experimental measurements, which are very encouraging results. Some coherent results should be highlighted:

• In the center of the honeycomb grid the speed is lower that in the sides. This is due to the physical obstacles present in the middle of the grid as shown in Fig 5, left. But also, due to the fact that the momentum of the gas provided by the turbine and the deflector is lower in the center. This effect is clearly visible in the top view of Fig 7: the farther away from the center, the faster flow.

• The gas speed is higher in the rear and the front of the rack in which no physical barriers are stablished. Nevertheless, these volumes does not play a role in the cooling of the metallic parts.

• The turbulence induced by high speed gas avoid creating "preferential" path in which the flow is laminar and established in steady state. This is the cause of the lack of linearity increasing or decreasing with regards to the speeds of Fig. 11.

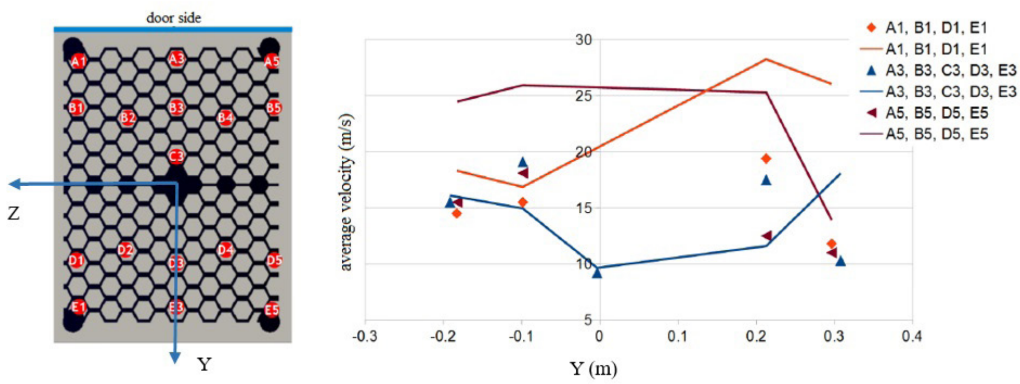


**Fig.11** - Comparison of experimental and simulated velocity at level 4. Dot: experiment, line: simulation

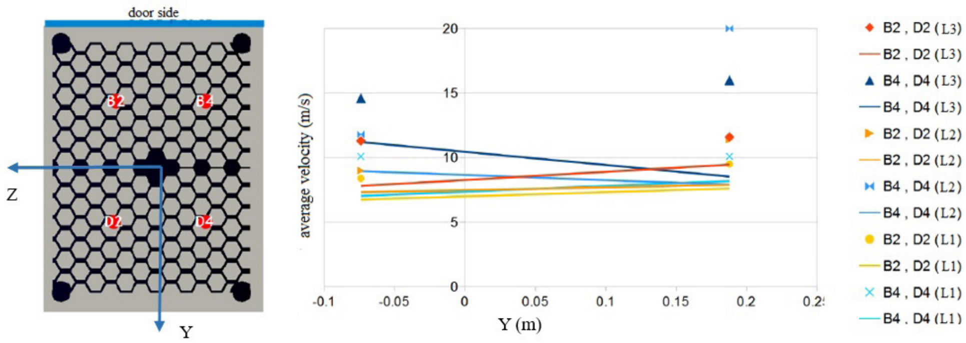


**Fig.12** - Comparison of experimental and simulated velocity at level 1, 2 and 3. Dot: experiment, line: simulation

As shown, very good experimental and numerical results have been obtained.

Nevertheless, for getting a more accurate comparison and improving our analysis, it is necessary to have the following information on the experimental data:

- Calibration procedure and uncertainty of the gas flow detectors.
- The error of the experiment produced by the repeatability of the experiment.
- The exact turbine flow rate and its variation in time.

As described, the turbulence in the chamber can induce a vibration in the flow speed measurement. Then, the experimental result can be an averaged value over a period of time (mean value), an instantaneous value whatever the value is, or the value obtained in steady state (if it is reached).

The key question is then, what is the standard deviation for the averaged gas velocity?

All this information is essential to find the error bar in the experiments. Without the error bar on the measurements, it is impossible to judge the quality of the experimental results. Hence, it is very complicated to perform an accurate comparison with simulations.

## Conclusion and future works

The gas quenching technology offers interesting opportunities for massive heat treatment of mechanical parts for automotive industry. This technique presents many advantages such as reduction the distortion of the load and close controlling of quenching intensity.

In order to optimise the gas quenching process, a comparison of experimental and simulation results has been conducted. Trials have been carried out in the industrial plateform of IRT M2P. Modeling of a quenching cell have been performed using the 3D CFD software qobeo®. The simulations evidenced a good agreement with measurements qualitatively (the same flow behavior inside the cell). Encouraging results have been obtained, the numerical results are of the same order of magnitude as the experimental ones for speed distributions at the 4 levels of the honeycomb grids of the cell. Nevertheless, the accuracy of experimental data used for the comparison should be improved, the uncertainty of the speed results should be taken into account. Hence, improvement of the experimental campaign is needed for more reliable comparison with the simulations. It would be very beneficial to perform PIV measurements.

The numerical results showed important differences in terms of speed and flow homogeneity between levels 4 and 1 of the rack. This could have a critical influence with regards to the quenching intensity of the metallic parts located in both grids, the final properties of the parts treated could present discrepancies. Assessing the effect of such flow difference on the mechanical properties of the metallic parts should be done in future works.

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