Thermocouple thermal inertia during refueling of hydrogen tanks: CFD validation

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Protocol for heavy-duty Hydrogen refuelling

Horizon 2020
European Union Funding
for Research & Innovation

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Context
PrHyde project

PrHyde: Protocol for heavy-duty Hydrogen refuelling

- Develop **recommendations** and **standardization** for **heavy duty refuelling protocol** for compressed gaseous hydrogen up to 700 bar
- Constraints for the protocols: fast, cost-effective and **safe**

Complementary approaches

- Experimental approaches (monitored refueling tests)
- Numerical approaches:
  - 0D/1D transient models (ex: SOFIL…)
  - **2D/3D Computational Fluid Dynamics (CFD) simulations**

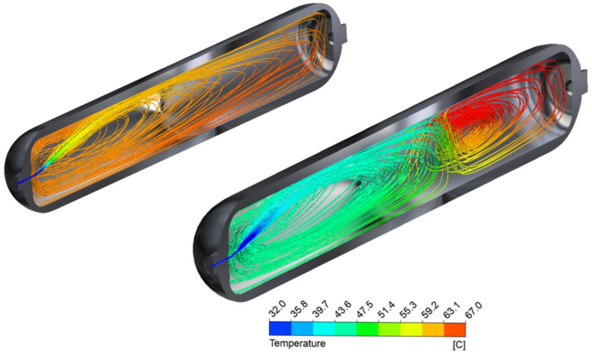
Context
Why CFD?

A safety recommendation from SAE J2601: $T_{gas} < 85°C$ everywhere

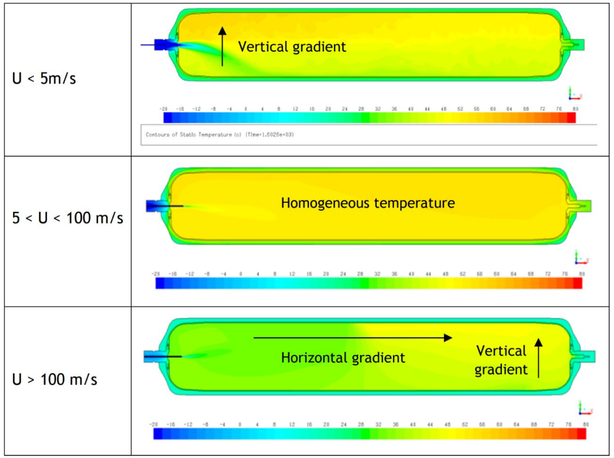
- Temperature gradient
- Various stratification regimes

CFD’s purpose in the project

- Build a reliable modeling strategy validated against experimental data
- Bring understandings to the physics involved during the refueling tests
- Give modeling recommendations

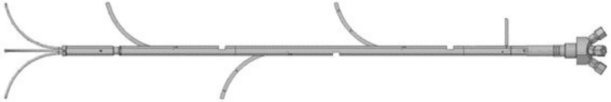


Different modeling parameters, different results



CFD results from HyTransfer project

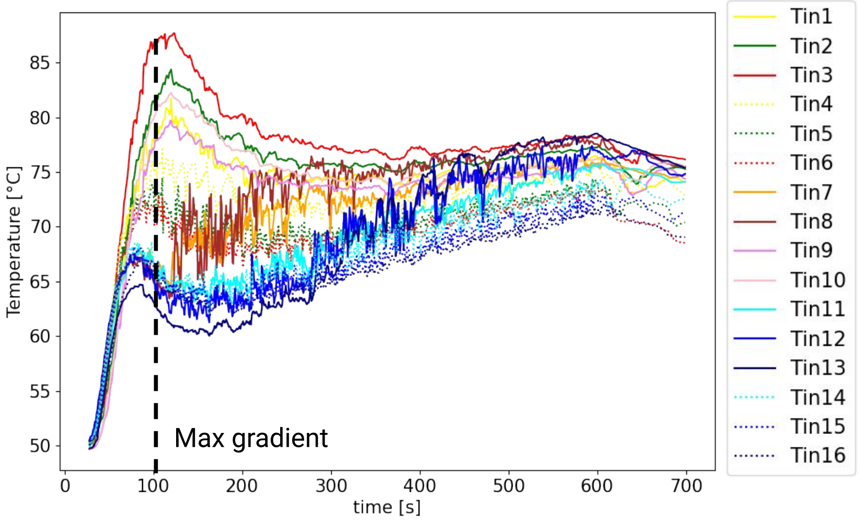
Case presentation
Experimental results



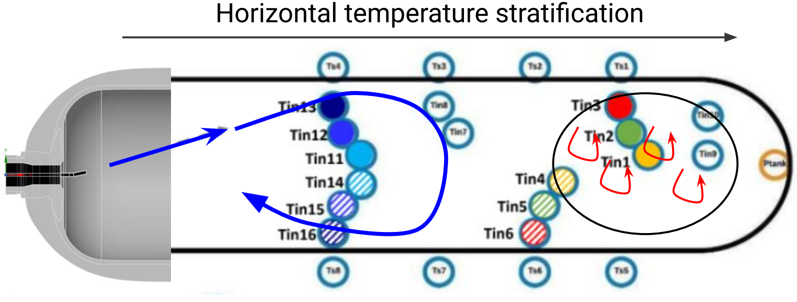
Filling of an Hexagon tank (165L - type IV), tested at Nikola Motor (June 2021)

- 20 to 700 bar in ~600s
- Gas is precooled to -40°C
- Injector tilted upwards
- **High temperature gradient** experimentally measured

Temperature at the different probes from experiment



Expected flow behaviour according to measurements @100s



Recirculation of the cold jet at the front of the tank

No mixing at the end of the tank

Case presentation
CFD model

Geometry

- 3D geometry - ½ volume of the tank

Models

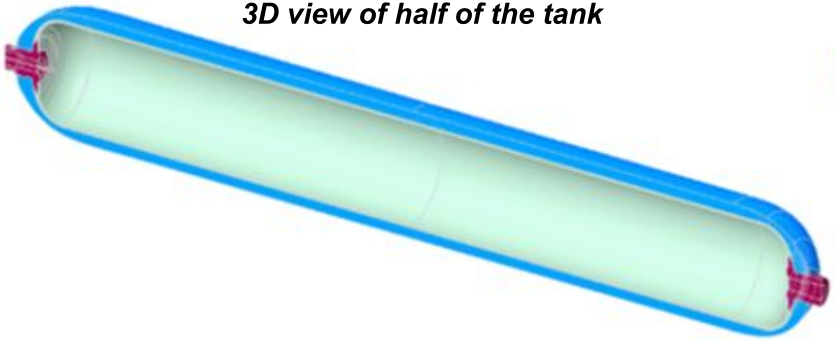
- CFD tool: ANSYS Fluent
- H_2 real gas from NIST tables ⇒ (P,T) dependent
- URANS + heat transfer
- Turbulent model: RSM
- Gravity

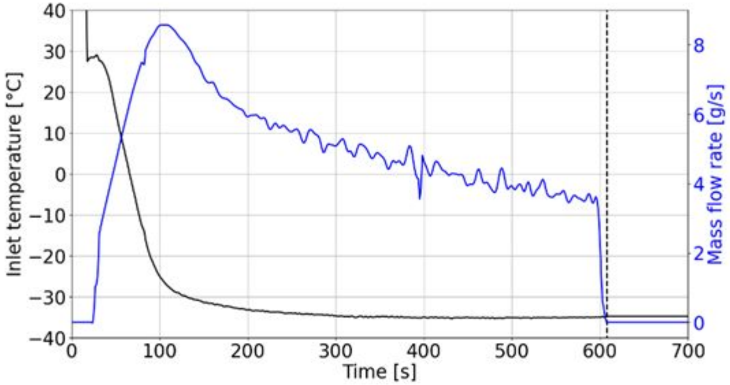
Boundary conditions for the CFD simulation from SOFIL

- Inlet mass flow rate and temperature
- Ambient temperature
- Heat exchange with ambient air
- Half tank with symmetry

CPU time: ~10000 hours

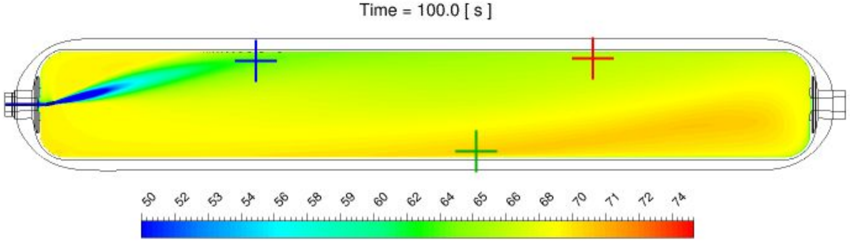
3D view of half of the tank



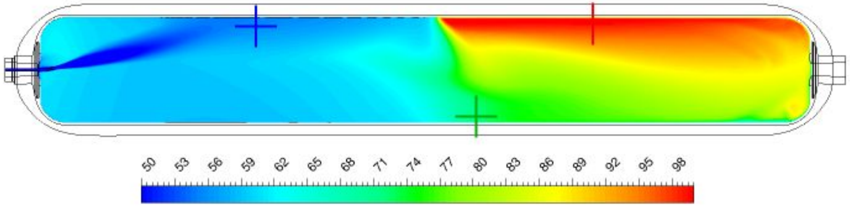


Unsteady inlet conditions

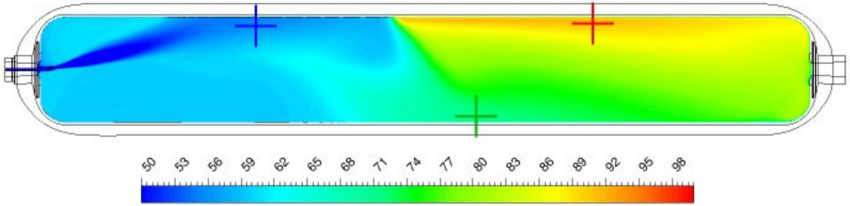
Results
Influence of the turbulence model[1]



k-ω model (400k cells hexa)



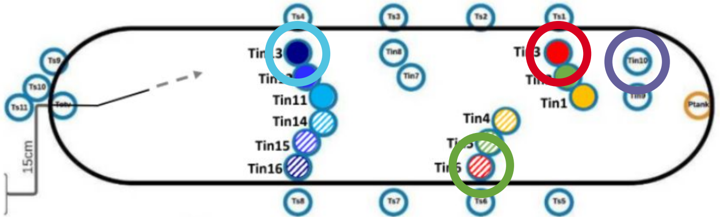
RSM model with coarse mesh (400k cells hexa, max y+ = 50)

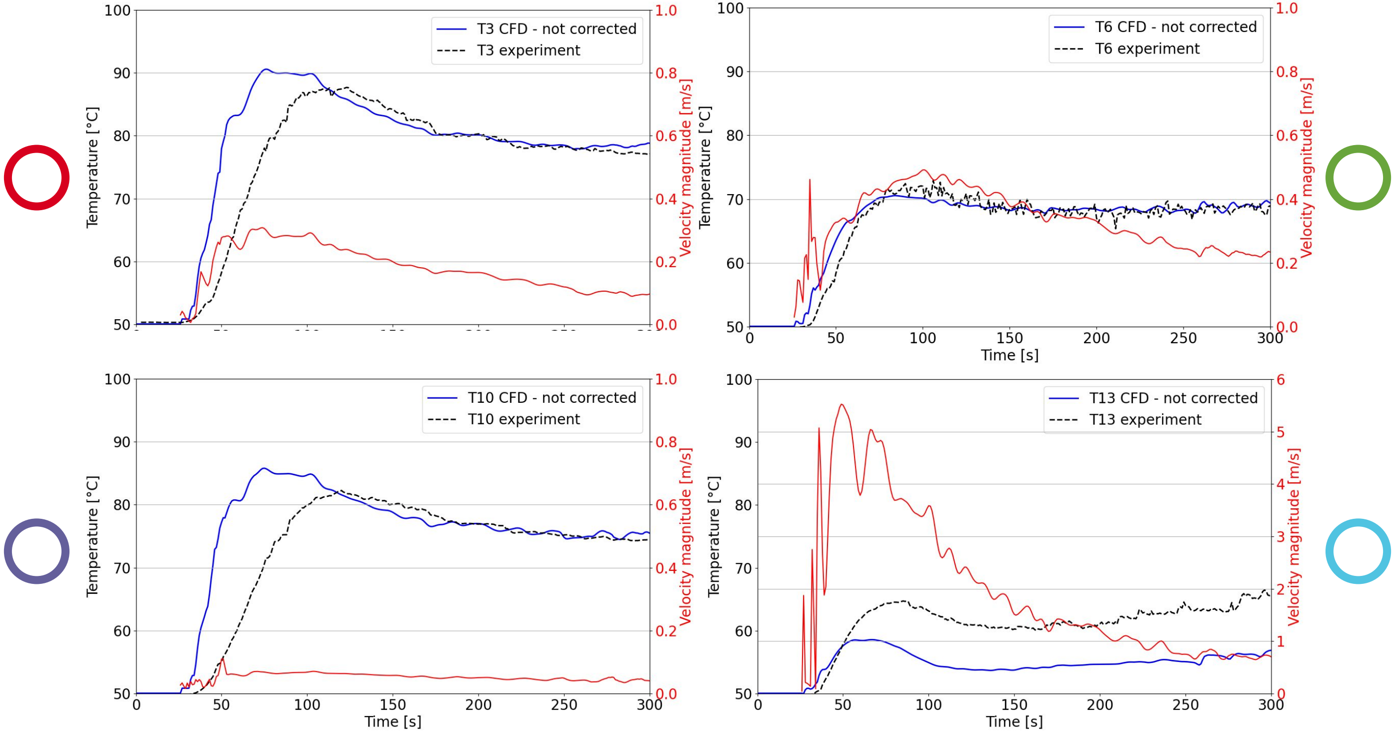


RSM model with refined mesh (800k cells hexa, max y+ = 10)

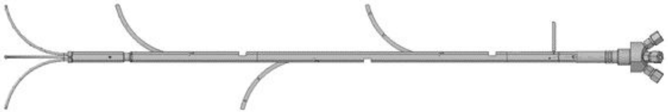
J. Martin et al., Influence of the turbulence model in the CFD simulation of hydrogen tank Filling by an impinging oblique jet, IJHE 2023

Results
Quantitative results





Results
The thermocouple delay model



Objective

- Estimate the delay between the temperature measured by the thermocouple and the gas temperature around it

Model

- With an energy balance applied on the thermocouple extremity, we have

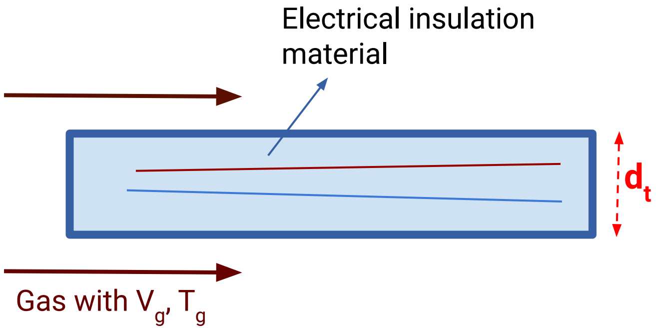
$$\frac{dT_t(t)}{dt} = \frac{1}{\tau_{cv}(t)}\left(T_g(t) - T_t(t)\right)$$

- τ_{cv} can be expressed as:

$$\tau_{cv}(t) = \frac{m_t Cp_t}{k_t(t) S_t}$$

- And the convective heat transfer coefficient:

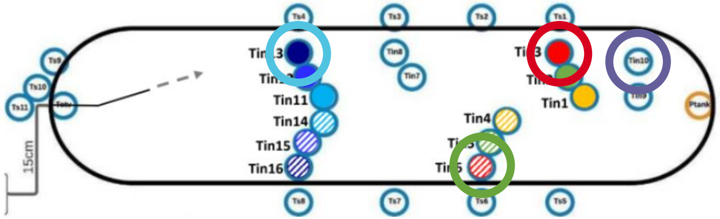
$$k_t(t) = f(Nu_t, \lambda_t, d_t)$$

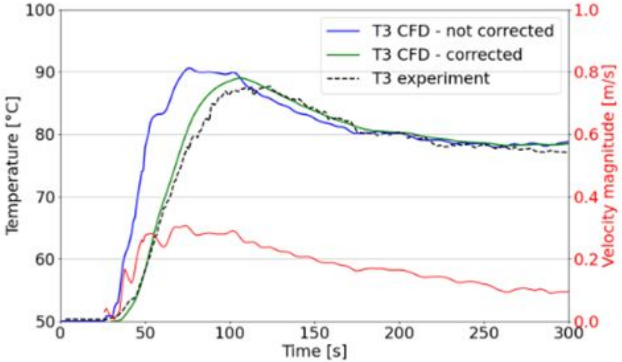


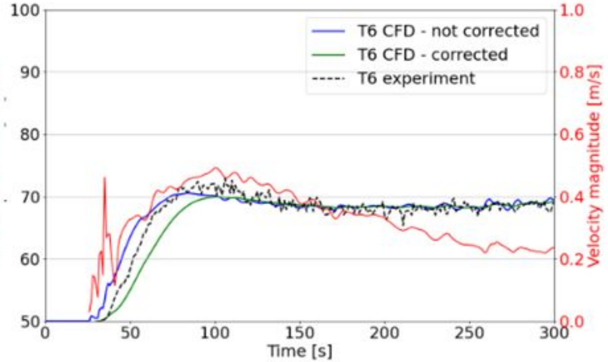
Schematic view of a thermocouple

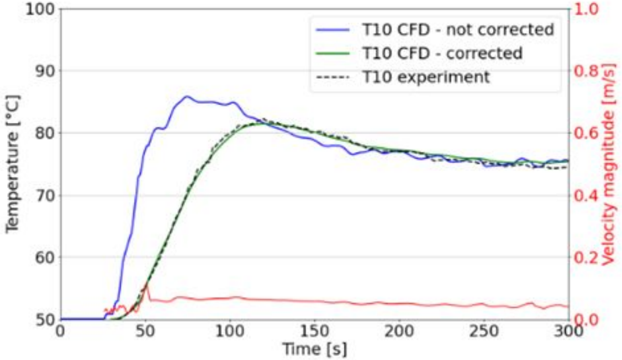
⇒ We have a relation between T_g and V_g (available with CFD) and T_t (measured)

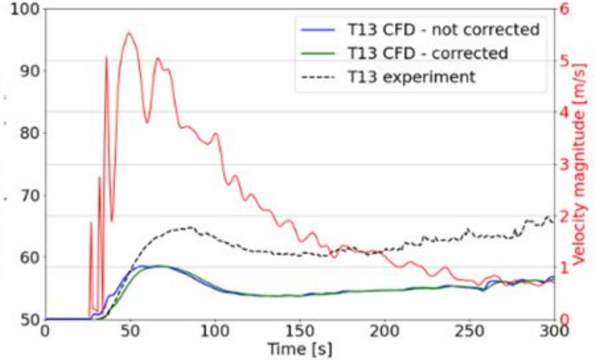
Results
Results with the thermocouple delay











Conclusion

On turbulence models

- Fairly good predictive performances for RSM for tilted injector configurations compared to eddy viscosity models
- A bit more expensive

On thermocouple thermal inertia

- A methodology has been proposed
- Part of the departure between the numerical and the experimental results has been recovered

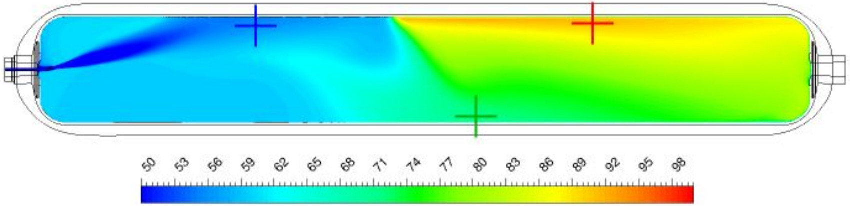
Perspectives

- The methodology can be further validated on other configurations (defueling cases, vertical tanks…)

Conclusion

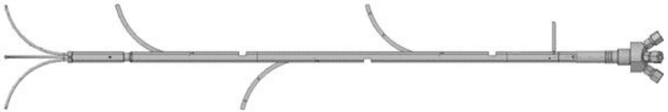
Thank you for you attention!

Contact: vincent.ren@airliquide.com



Model

The thermocouple delay model



Numerically

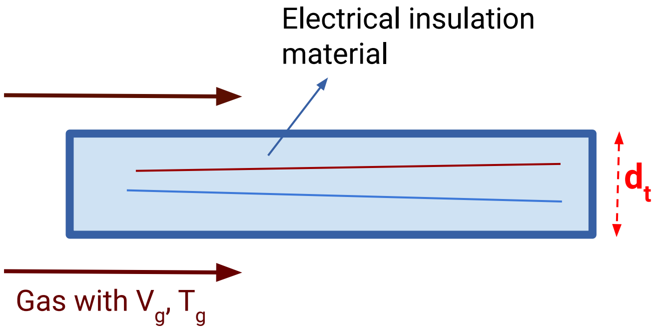
- τ_{cv} can be written as a function of d_t

$$\tau_{cv}(t) = \frac{m_t C p_t}{k_t(t) S_t} = \frac{\rho_t V_t C p_t}{k_t(t) S_t} \approx \frac{\rho_t d_t C p_t}{4 k_t(t)}$$

- k_t is calculated with Nusselt correlation [1]

$$k_t = \frac{Nu_{d_t} \lambda_g}{d_t}$$

$$Nu_{d_t} = 0.3 + \frac{0.62 Re_{d_t}^{1/2} \mathrm{Pr}^{1/3}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} \left[1 + \left(\frac{Re_{d_t}}{282000}\right)^{5/8}\right]^{4/5}$$

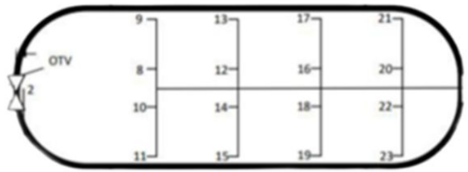


Schematic view of a thermocouple

⇒ We have a relation between T_g and V_g (available with CFD) and T_t (measured)

[1] S. W. Churchill and M. Bernstein (1977)

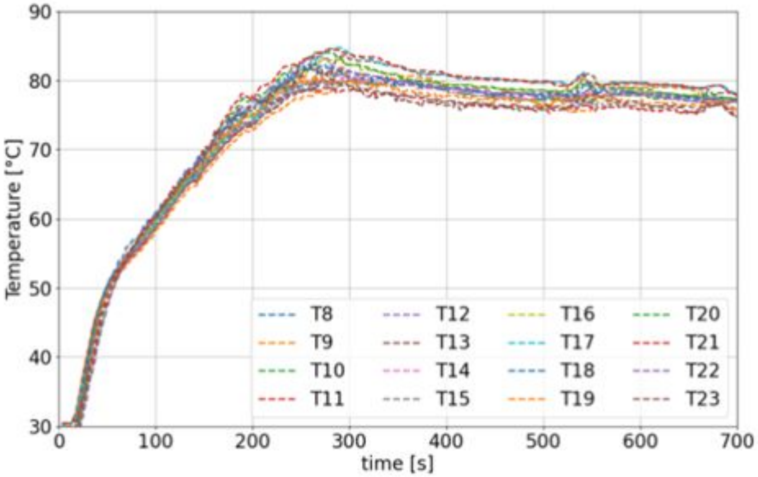
Another case
Experimental results



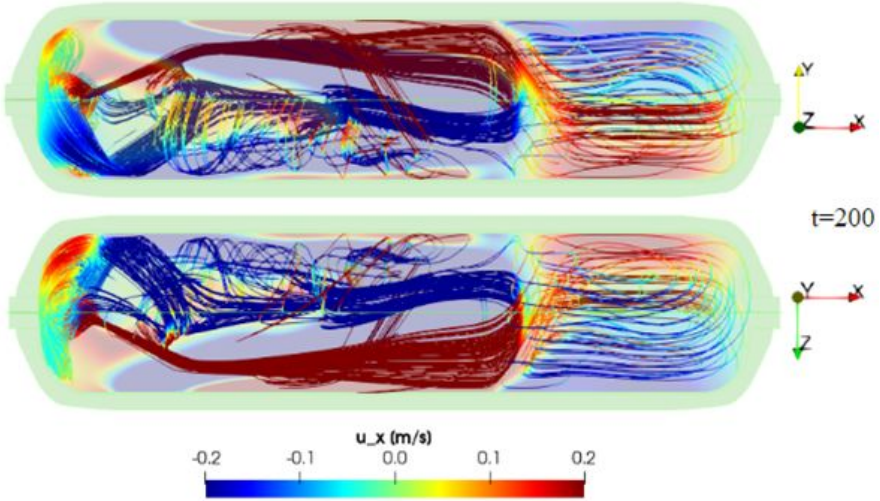
Filling of an Hexagon tank (240L - type IV)

- 20 to 700 bar in ~700s
- Gas is precooled to -30°C
- **Injector tilted upwards and sideways**

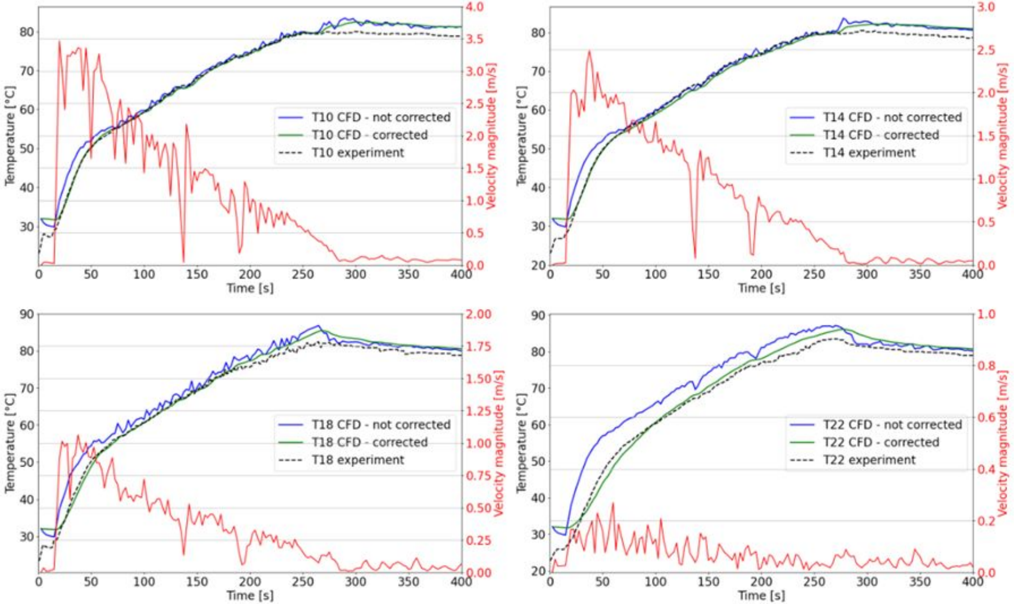
Temperature at the different probes from experiment

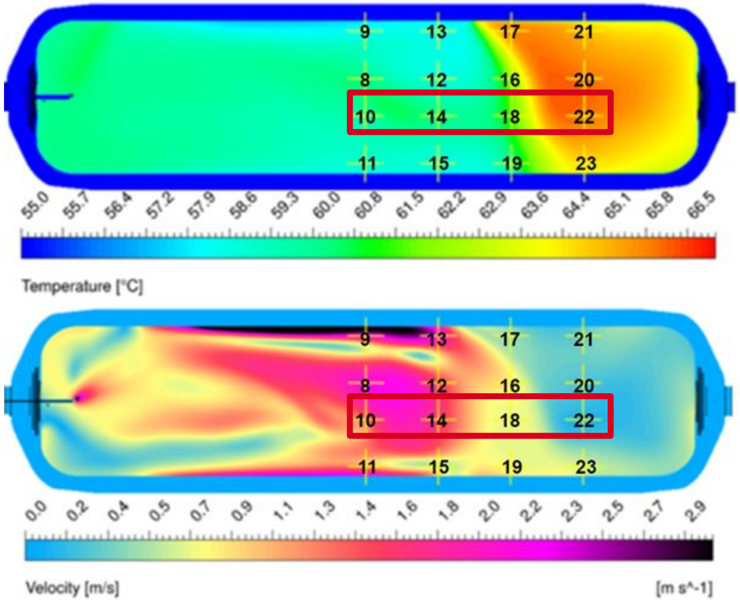


Corresponding CFD results @200s



Another case
Quantitative results with the thermocouple correction





Temperature and velocity fields @200s