Buoyant jet model to predict a vertical thermal stratification during refueling of gaseous hydrogen tanks in horizontal position with axial injection

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2. *Institut de mécanique des fluides de Toulouse (IMFT), 2 allée Camille Soula, Toulouse, 31400, France*

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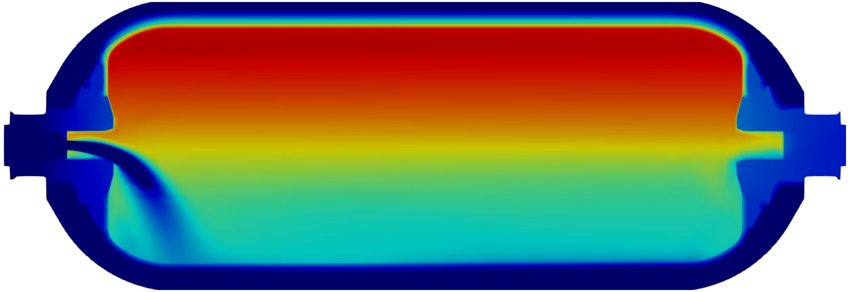
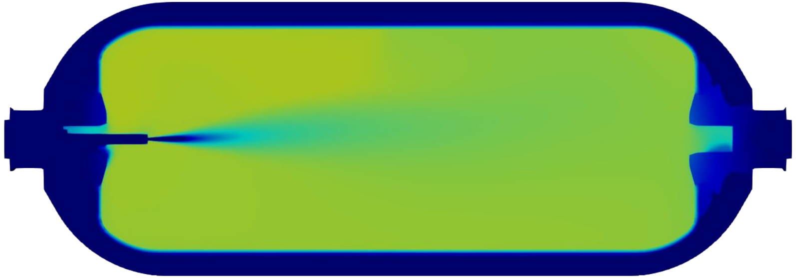


Vertical thermal stratification



Homogeneous thermal field

Context

Context

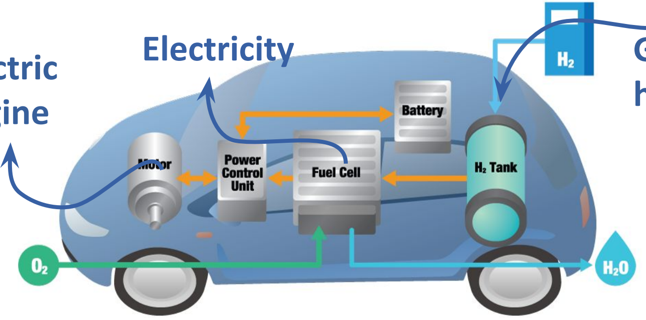
- Hydrogen for mobility

https://www.leaseplan.com/

Tank size	122.4[*] L
Tank pressure	700[*] bar
Hydrogen mass	5[*] kg
Autonomy	550[*] km
Filling time	3-5 min

At 15°C and 701.013 bara, ρ = 40.21 kg/m^3

Doc press Air Liquide



Electric engine

Electricity

Gaseous hydrogen

Oxygen from ambient environment

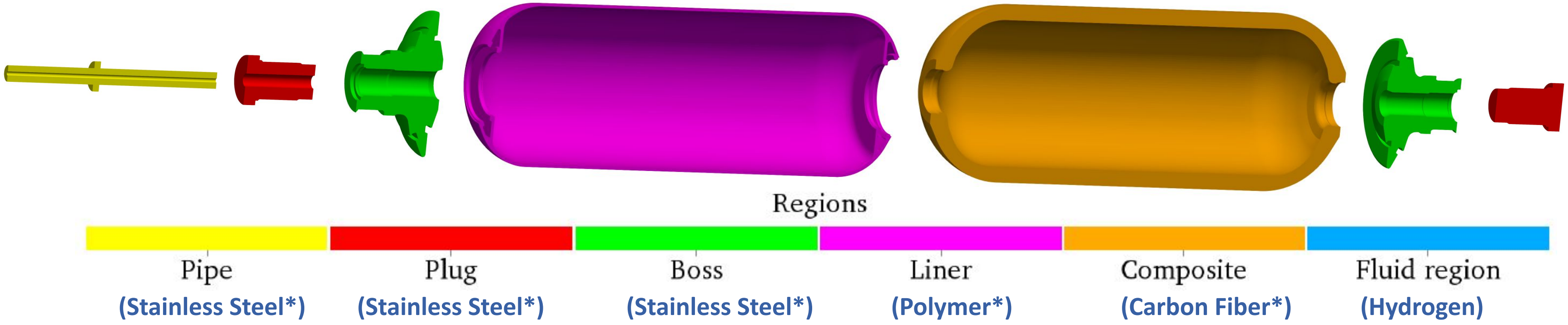
Reject water

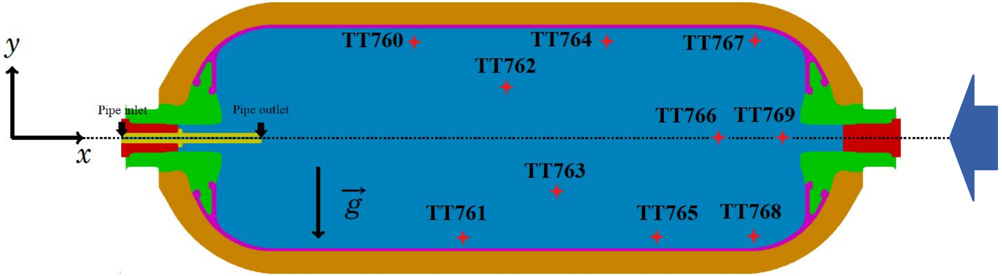
Adapted from: https://genh2hydrogen.com/hydrogen-cars/

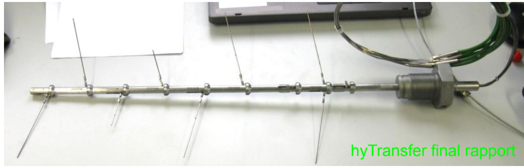
*https://www.toyota-europe.com/download/cms/euen/Toyota%20Mirai%20FCV_Posters_LR_tcm-11-564265.pdf

Context

- Description of a hydrogen tank





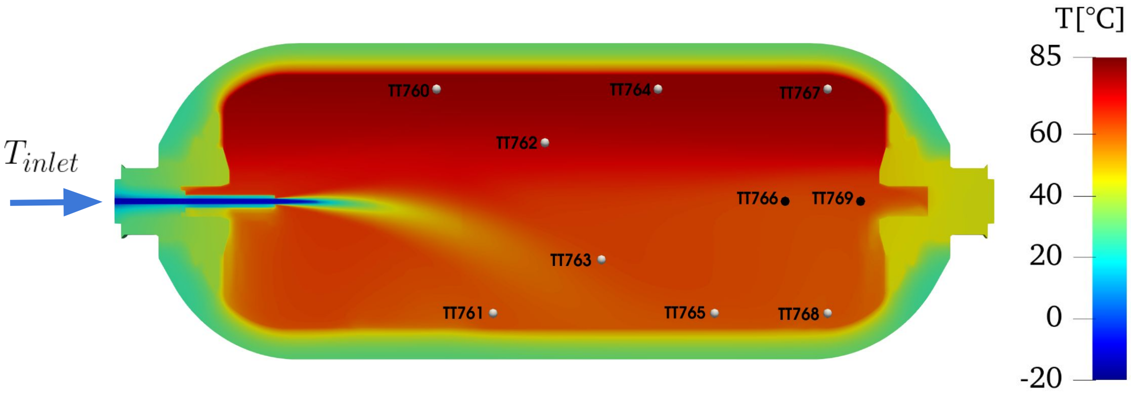


*for the type IV 37 L tank provided by Lincoln Hexagon

Context

- **Tank filling mechanism**

Injecting hydrogen in a closed volume: Pressure ⇧ Temperature ⇧



Recommendation from SAE J2601

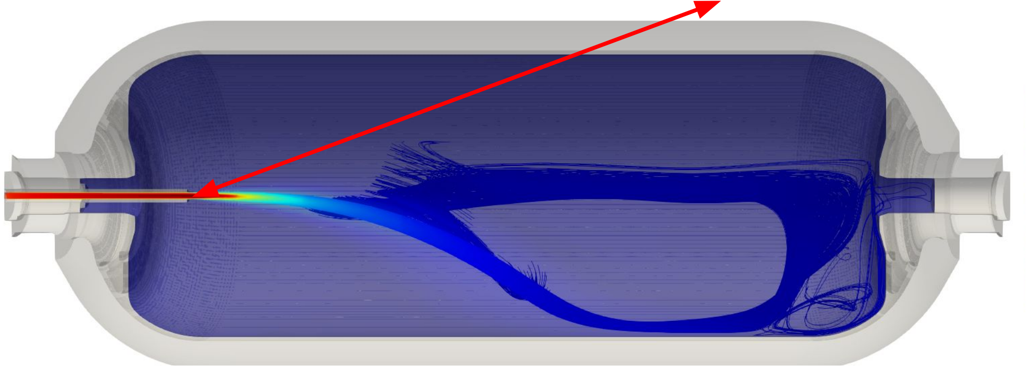
Parameters	Limits
Gas temperatures	[-40°C, 85°C]
Gas pressures	[5 bar, 875 bar]
Mass flowrate	60 g/s

Context

- **Previous results on thermal gradients**

❖ Terada et al. (2008)

➢ The criterion 5 m/s at the inlet velocity is suggested to detect thermal gradient onset for hydrogen tank



Illustrative image **not issue from Terada study.**

“Hydrogen gas in the tank is agitated and the internal temperature of the tank is uniformed when the gas jet velocity is high. If the gas jet velocity decreases to 5 m/s then the fluid behavior in the tank changes and convection dominates over agitation, causing distribution of temperatures and the temperature in the upper area of the tank rises.”

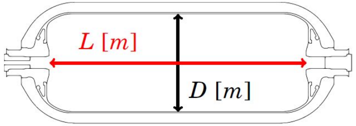
Terada, Toshihiro, Hiroshi Yoshimura, Yohsuke Tamura, Hiroyuki Mitsuishi, et Shogo Watanabe. « Thermal Behavior in Hydrogen Storage Tank for Fcv on Fast Filling (2nd Report) », 2008-01-0463, 2008. https://doi.org/10.4271/2008-01-0463.

Context

- **Observation of vertical thermal gradients**

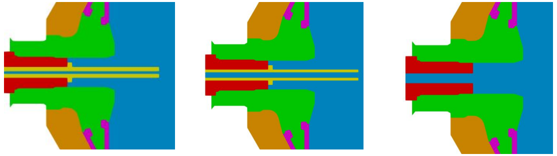
HyTransfer

Pre-Normative Research on Gaseous Hydrogen Transfer

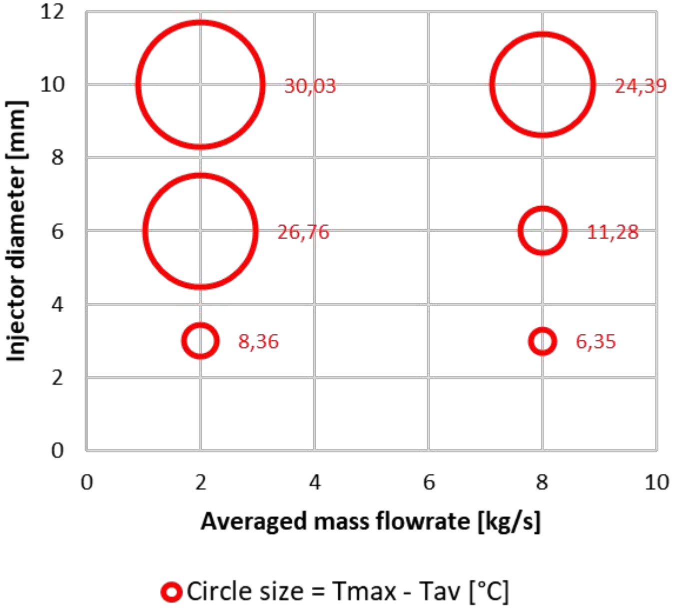


Type IV 37 L tank provided by Lincoln Hexagon with a L/D = 2.4

Diameter: 3 mm **6 mm** **10 mm**



Averaged mass flowrate: 8 g/s (filling time ≈ 160 s)
2 g/s (filling time ≈ 600 s)



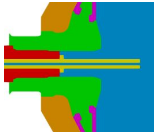
HyTransfer conclusion: The smaller the inlet gas velocity; the larger the vertical thermal gradients. The criterion 5 m/s at the inlet velocity works for the 37 L tank.

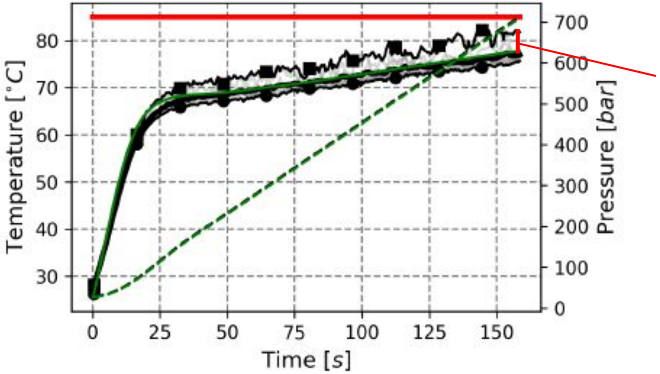
Context

- Two extreme scenarios with experimental results

D3Q8: Homogeneous case

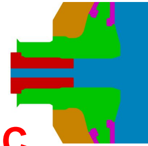
- Tank capacity: 37 L
- Injection diameter: 3 mm
- Average filling rate: 8 g/s
- injection pipe

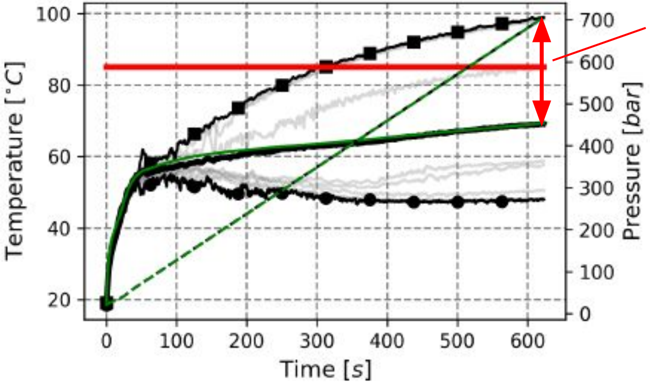


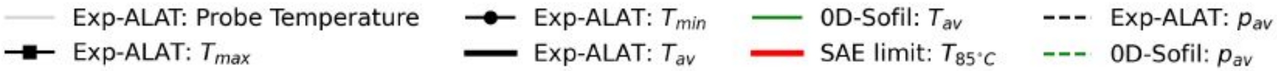


D10Q2: Heterogeneous case

- Tank capacity: 37 L
- Injection diameter: 10 mm
- Average filling rate: 2 g/s
- No injection pipe





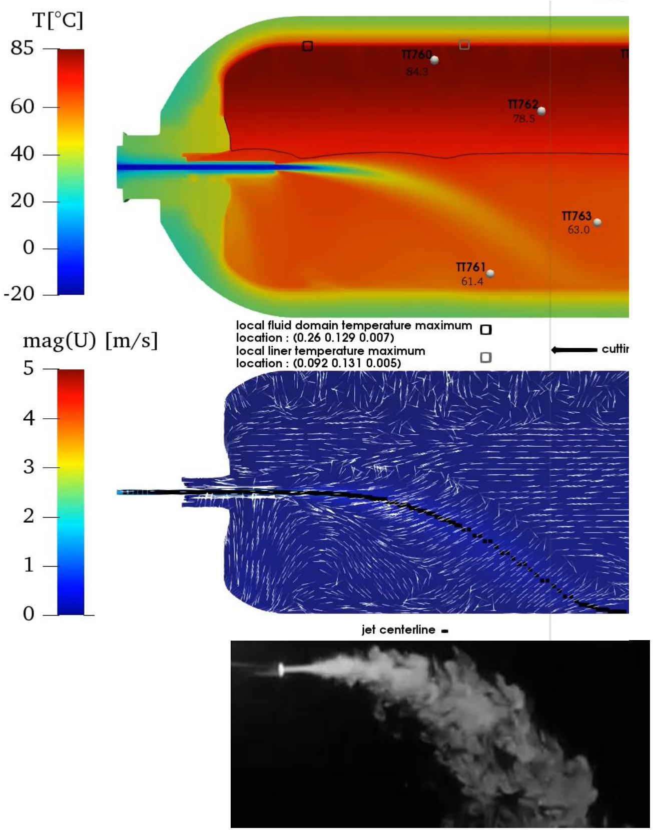


- *ALAT = Air Liquide Advanced Technology*
- *Temperatures are gas temperatures*


Ozeair Abessi (2014)
https://www.youtube.com/watch?v=90P7oJdCtGc

Round buoyant jet theory

Buoyant Jet model



Buoyant Jet model

Round buoyant jet theory

Buoyant Jet model

- **Computational Fluid Dynamics visualisations**

Type IV

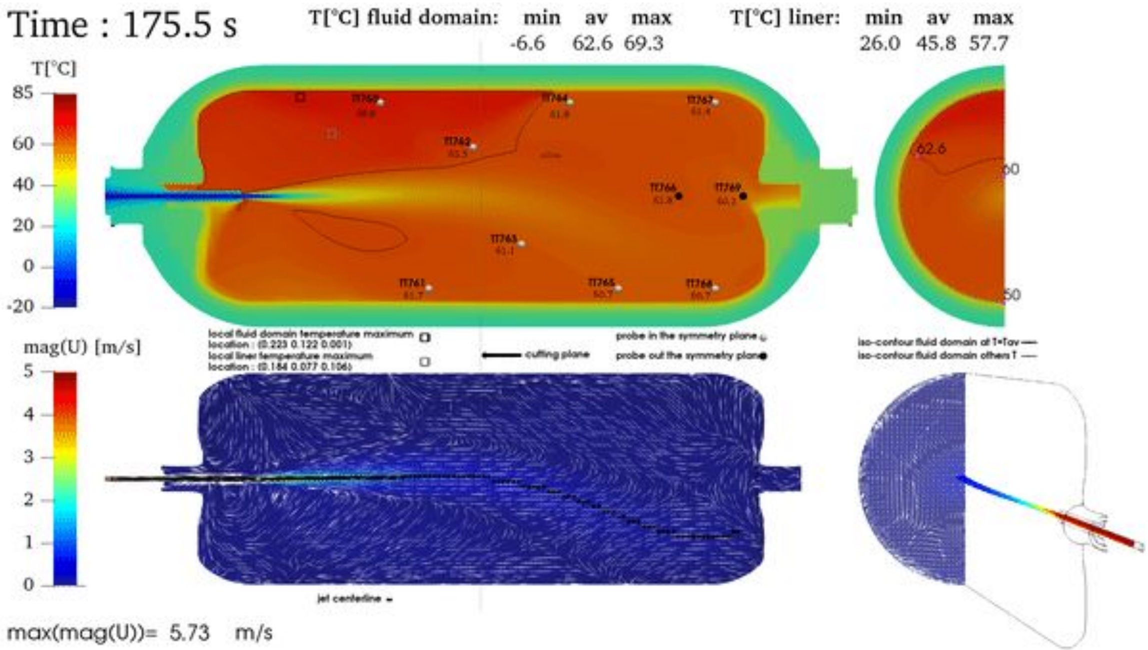
Inner volume = 36.7 L

L/D ratio = 2.4

Injector diameter = 6 mm

Filling time ≈ 600 s

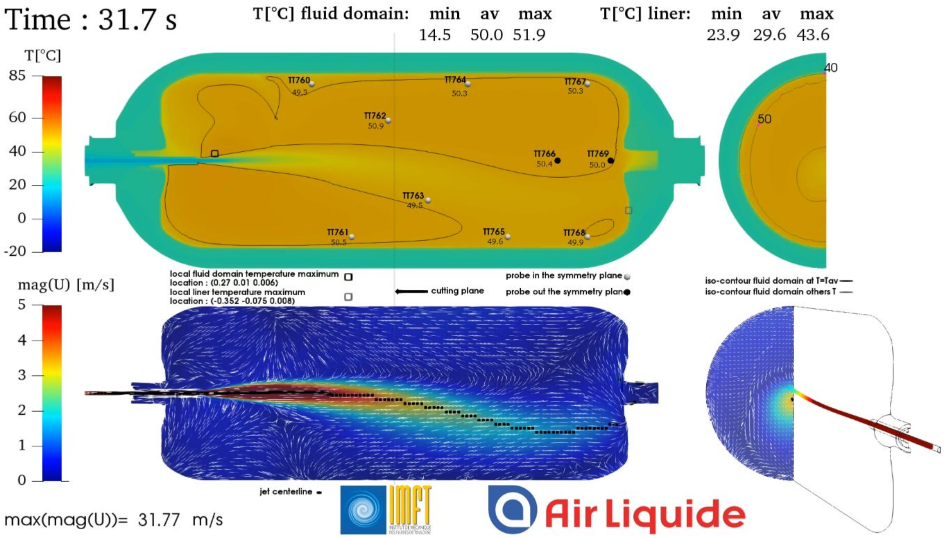
Averaged mass flowrate ≈ 2 g/s

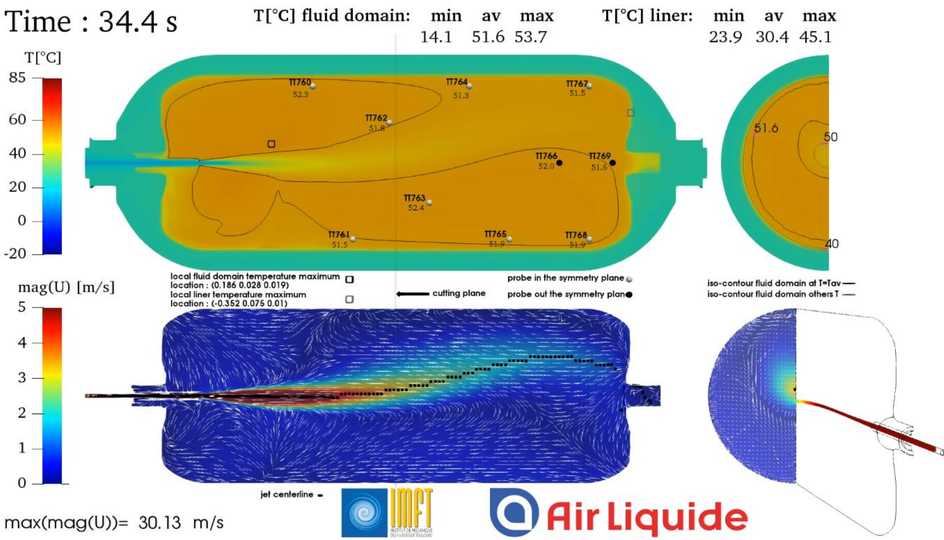


<u>CFD results issued from :</u> *Gonin, R., Horgue, P., Guibert, R., Fabre, D., Bourguet, R., Ammouri, F. and Vyazmina, E., Advanced turbulence modeling improves thermal gradient prediction during compressed hydrogen tank filling, International Journal of Hydrogen Energy, 2023.*

Buoyant Jet model

- **Computational Fluid Dynamics visualisations**
  - **Jet oscillations**





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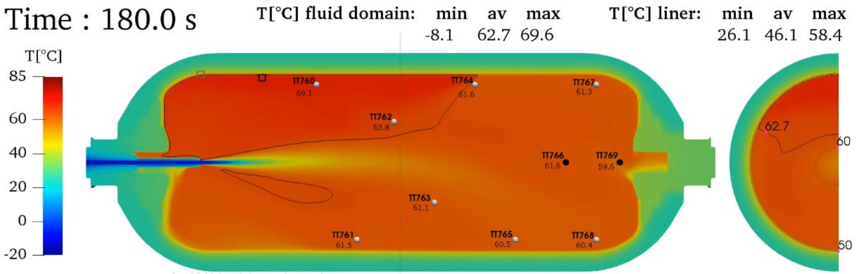
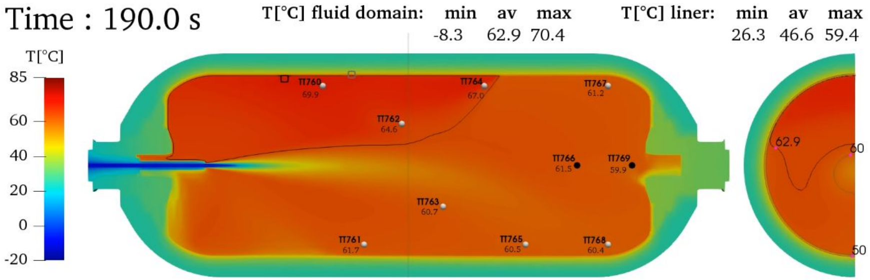
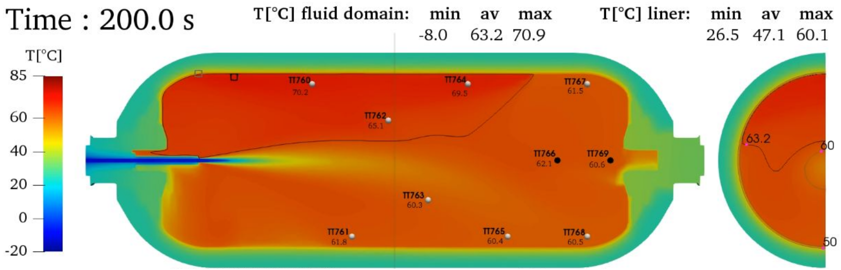
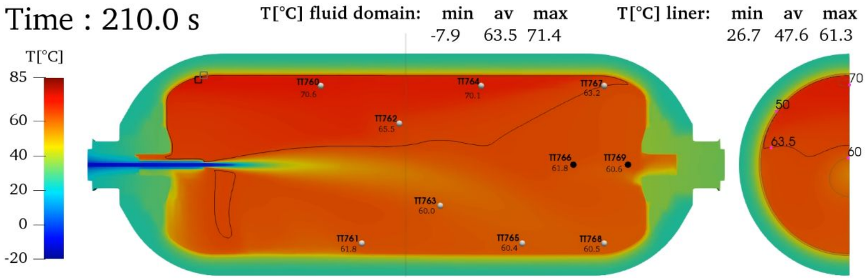
Buoyant Jet model

- **Computational Fluid Dynamics visualisations**
  - **Thermal gradient occurrence when jet hitting the lower part of the tank**





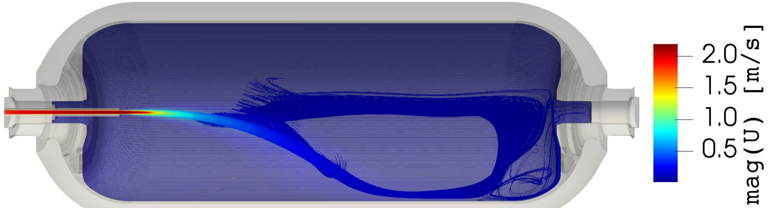


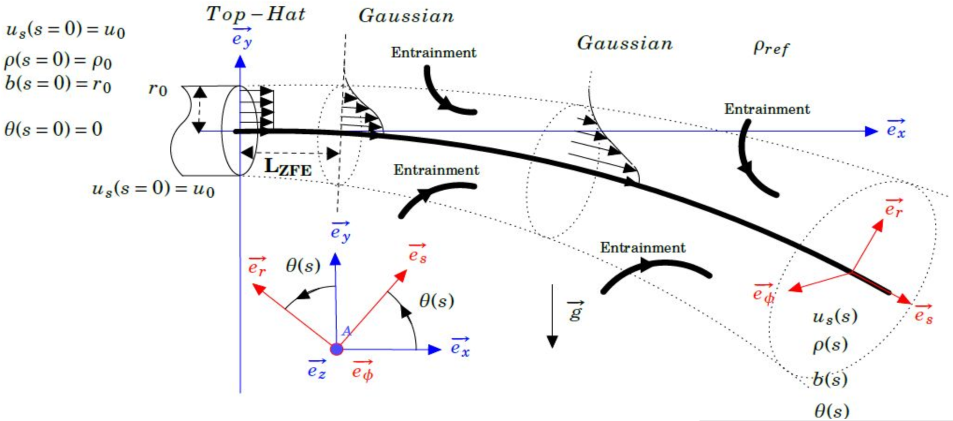


CFD results issued from : *Gonin, R., Horgue, P., Guibert, R., Fabre, D., Bourguet, R., Ammouri, F. and Vyazmina, E., Advanced turbulence modeling improves thermal gradient prediction during compressed hydrogen tank filling, International Journal of Hydrogen Energy, 2023.*

Buoyant Jet model

• Modeling





Hypotheses :

- Steady-state
- Uniform pressure
- Viscosity term neglected
- Boussinesq approximation
- Velocity and density profiles imposed
- Self-similarity
- Entrainment rate modeled

Physical quantities	Initial conditions
Mass flux	$Q(L_{ZFE}) = 1.72\pi r_0^2 u_0$
Momentum flux	$M(L_{ZFE}) = \pi u_0^2 r_0^2$
Buoyancy flux	$J(L_{ZFE}) = \dfrac{\lambda^2}{\lambda^2+1} Q(L_{ZFE}) \dfrac{\rho_{grad}(0)-\rho_0}{\rho_{ref}} g$
Jet deviation angle	$\theta(L_{ZFE}) = 0$
Jet trajectory coordonate	$x(L_{ZFE}) = L_{ZFE} = 9{,}79\ r_0$ $y(L_{ZFE}) = 0$

Equation system

$$\boxed{\frac{\partial Q}{\partial s} = (8\pi M)^{1/2}\alpha}$$

Entrainment rate modeled

$$\frac{\partial M}{\partial s} = (\lambda^2+1)\frac{JQ}{2M} sin(\theta)$$

Linear stratified environment

$$\boxed{\frac{\partial J}{\partial s} = Q\frac{g}{\rho_{ref}}\frac{\partial \rho_{grad}(y)}{\partial y} sin(\theta)}$$

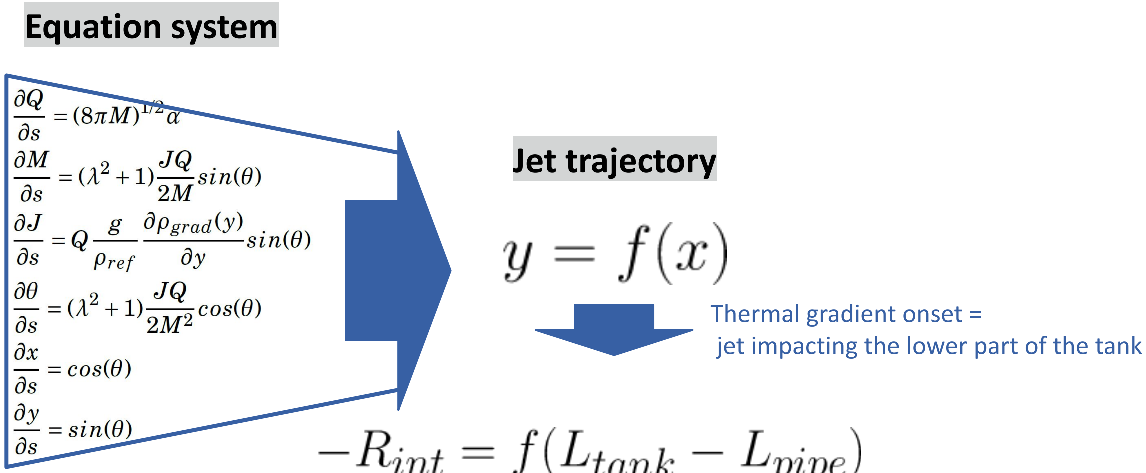
$$\frac{\partial \theta}{\partial s} = (\lambda^2+1)\frac{JQ}{2M^2} cos(\theta)$$

$$\frac{\partial x}{\partial s} = cos(\theta)$$

$$\frac{\partial y}{\partial s} = sin(\theta)$$

Buoyant Jet model

- **Froude number**



Equation system

$$\frac{\partial Q}{\partial s} = (8\pi M)^{1/2}\alpha$$

$$\frac{\partial M}{\partial s} = (\lambda^2+1)\frac{JQ}{2M}sin(\theta)$$

$$\frac{\partial J}{\partial s} = Q\frac{g}{\rho_{ref}}\frac{\partial \rho_{grad}(y)}{\partial y}sin(\theta)$$

$$\frac{\partial \theta}{\partial s} = (\lambda^2+1)\frac{JQ}{2M^2}cos(\theta)$$

$$\frac{\partial x}{\partial s} = cos(\theta)$$

$$\frac{\partial y}{\partial s} = sin(\theta)$$

Jet trajectory

$$y = f(x)$$

Thermal gradient onset =
jet impacting the lower part of the tank

$$-R_{int} = f(L_{tank} - L_{pipe})$$

Buoyant Jet model

- Froude number

Equation system

$$\begin{cases} \dfrac{\partial Q}{\partial s} = (8\pi M)^{1/2}\alpha \\ \dfrac{\partial M}{\partial s} = (\lambda^2+1)\dfrac{JQ}{2M} sin(\theta) \\ \dfrac{\partial J}{\partial s} = Q\dfrac{g}{\rho_{ref}}\dfrac{\partial \rho_{grad}(y)}{\partial y} sin(\theta) \\ \dfrac{\partial \theta}{\partial s} = (\lambda^2+1)\dfrac{JQ}{2M^2} cos(\theta) \\ \dfrac{\partial x}{\partial s} = cos(\theta) \\ \dfrac{\partial y}{\partial s} = sin(\theta) \end{cases}$$

Simplified equation system

$$\begin{cases} \dfrac{dQ}{ds} = (8\pi M)^{\frac{1}{2}}\alpha \\ \dfrac{dM}{ds} = 0 \\ \dfrac{dJ}{ds} = 0 \\ \dfrac{d\theta}{ds} = (\lambda^2+1)\dfrac{JQ}{2M^2} \\ x = s \\ y = \theta \end{cases}$$

Jet trajectory

$$y = (\lambda^2+1)\frac{J(L_{ZFE})}{2M(L_{ZFE})^2}(x - L_{ZFE})\left[Q(L_{ZFE}) + 4\pi M^{\frac{1}{2}}\alpha(x - L_{ZFE})\right]$$

Thermal gradient onset =
jet impacting the lower part of the tank

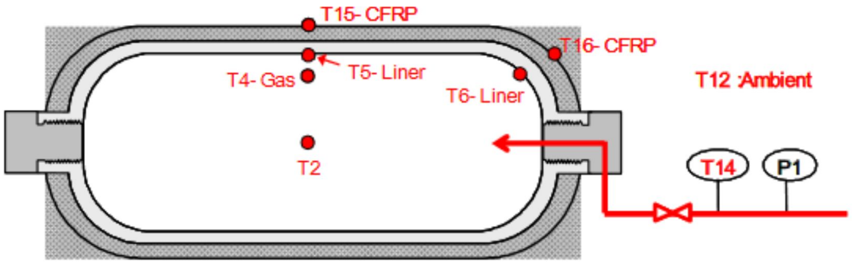
$$\begin{cases} R_{tank} = (\lambda^2+1)\dfrac{\rho_{ref}-\rho_0}{\rho_{ref}}\dfrac{g\tilde{L}^2}{u_0^2}\left(0.37 + 0.23\dfrac{\tilde{L}}{r_0}\alpha\right) \\ \tilde{L} = L_{tank} - L_{inj} - L_{ZFE} \end{cases}$$

Froude number construction

$$Fr = \frac{u_0}{\sqrt{\frac{\rho_{ref}-\rho_0}{\rho_{ref}} g \frac{\tilde{L}^2}{R_{tank}}\left(0.74+0.0223\frac{\tilde{L}}{r_0}\right)}}$$

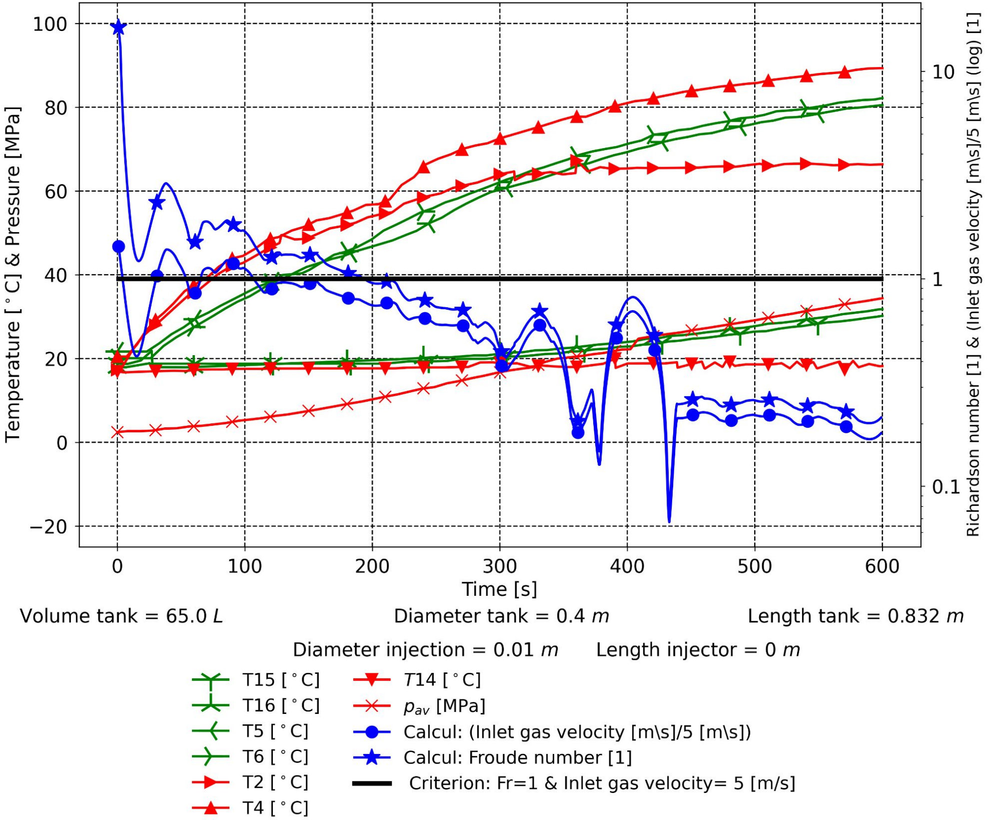
Buoyant Jet model

- **Results**



Type IV
Inner volume 65L
L/D = 2.08

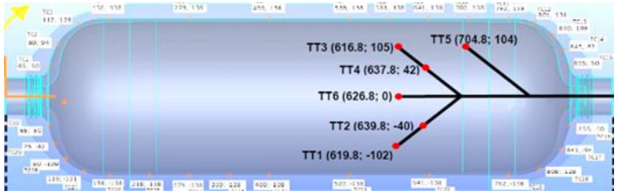
Terada, Toshihiro, Hiroshi Yoshimura, Yohsuke Tamura, Hiroyuki Mitsuishi, et Shogo Watanabe. « Thermal Behavior in Hydrogen Storage Tank for Fcv on Fast Filling (2nd Report) », 2008-01-0463, 2008. https://doi.org/10.4271/2008-01-0463.



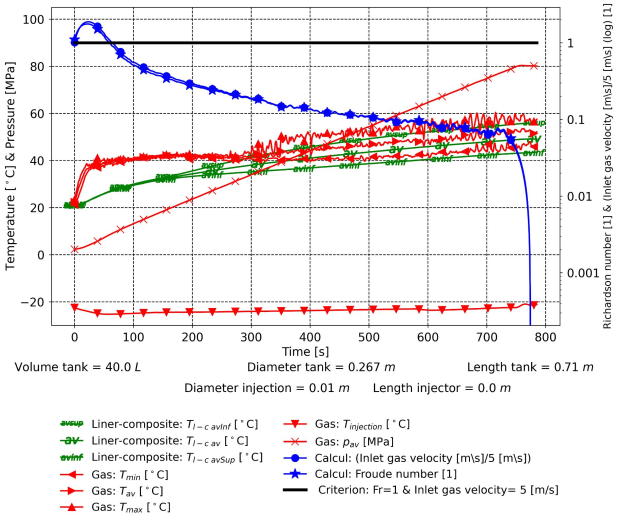
Buoyant Jet model

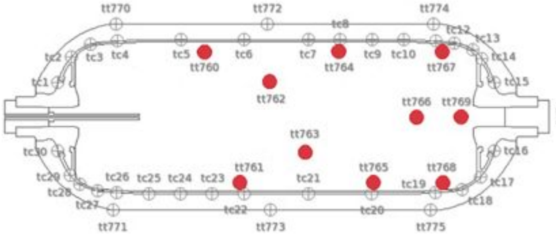
- **Results**

Type	Volume [L]	Ratio L/D
III	40	2.7
IV	36.7	2.4
IV	531	5.6

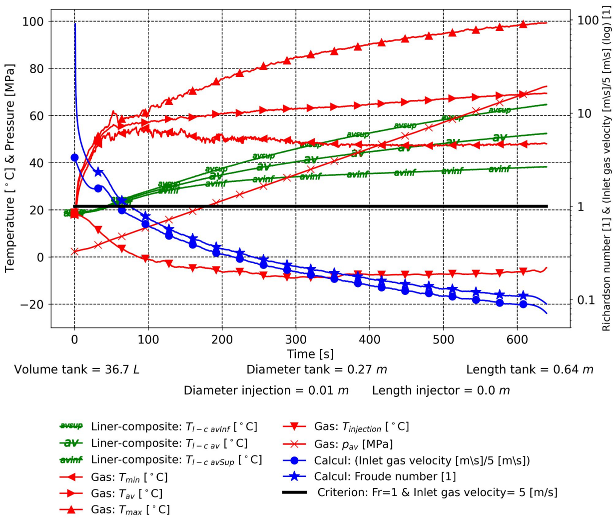


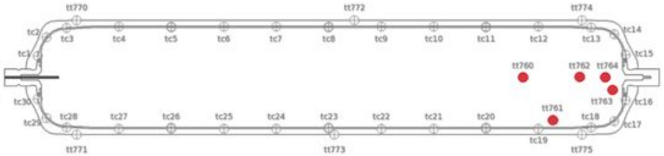
40 L



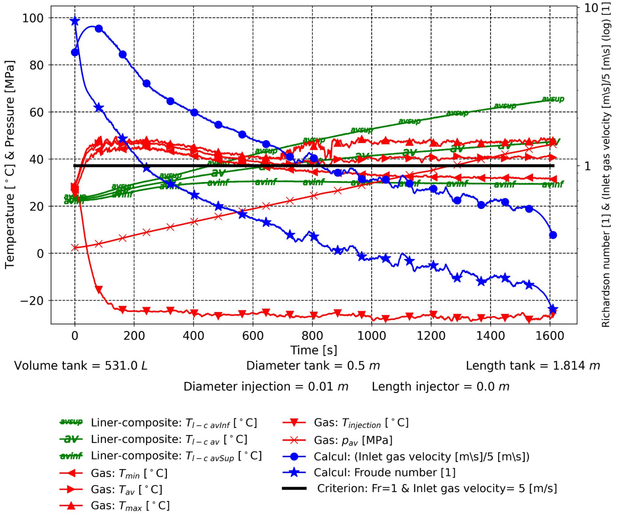


36.7 L





531 L



Buoyant Jet model

- **Conclusions**

✓ For some filling conditions of horizontal tanks, experimental measurements showed **thermal stratification can reach 30°C between the maximal gas temperature and the average gas temperature**

✓ Thermodynamic based model (**0D model**) can only **predict the volume averaged gas temperature in the tank**

✓ In the literature, only **Terada** gave a **minimal limit of 5 m/s** for the **gas velocity at the injection**, **to avoid thermal stratification in horizontal hydrogen tank with axial injection** based on experimental study using a type IV 65 liter tank

✓ Using a phenomenological approach, a buoyant jet model is used to suggest a **Froude number limit of 1** considering the filling conditions and the tank geometry to predict thermal stratification

✓ This **Froude number minimal limit of 1** is **consistent** with the **Terada criteria for small aspect ratio tanks**. **It gives better predictions for longer aspect ratio tanks**.


Thank
You!