Air Liquide

MODELING FOR THE DEVELOPMENT OF HEAVY DUTY REFUELING PROTOCOLS

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PRHYDE project partners

No.	Participant organisation name	Short name	Country
1	Ludwig-Bölkow-Systemtechnik GmbH (Coordinator)	LBST	DE
2	Zentrum für BrennstoffzellenTechnik GmbH	ZBT	DE
3	Air Liquide SA	AL	FR
4	Engie Lab CRIGEN	ENGIE	FR
5	Toyota Motor Europe NV	TME	BE
6	ITM Power (Trading) Limited	ITM	UK
7	NEL Hydrogen AS	NEL	DK
8	Shell Deutschland Oil GmbH	SHELL	DE
9	Commissariat à l'énergie atomique et aux énergies alternatives	CEA	FR
10	Nikola Motor Company	Nikola	USA

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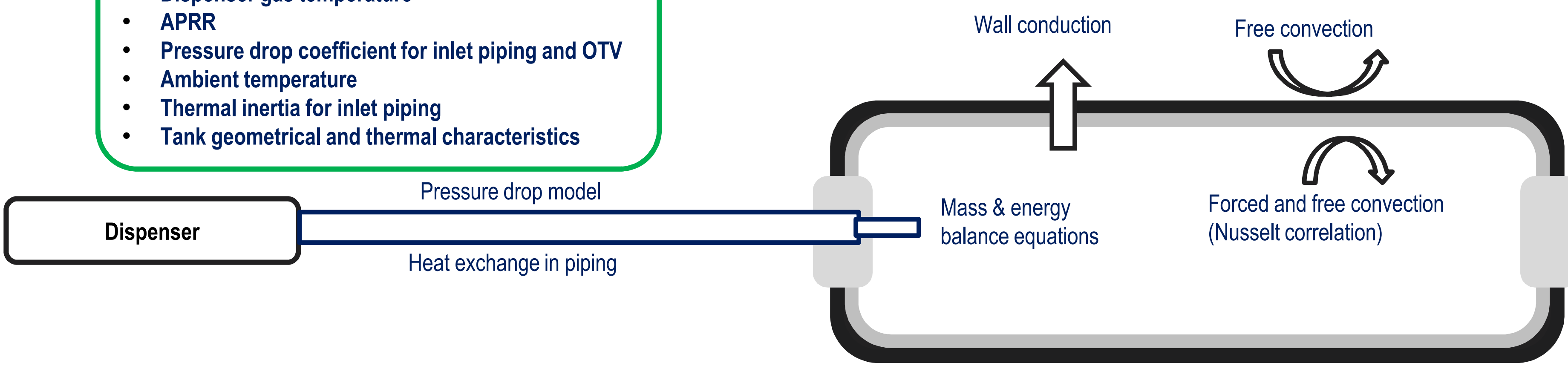
SOFIL(Air Liquide) and HyFILL (Engie) softwares (unsteady state 0D gas - 1D tank walls)

Inputs
- **Dispenser gas temperature**
- **APRR**
- **Pressure drop coefficient for inlet piping and OTV**
- **Ambient temperature**
- **Thermal inertia for inlet piping**
- **Tank geometrical and thermal characteristics**



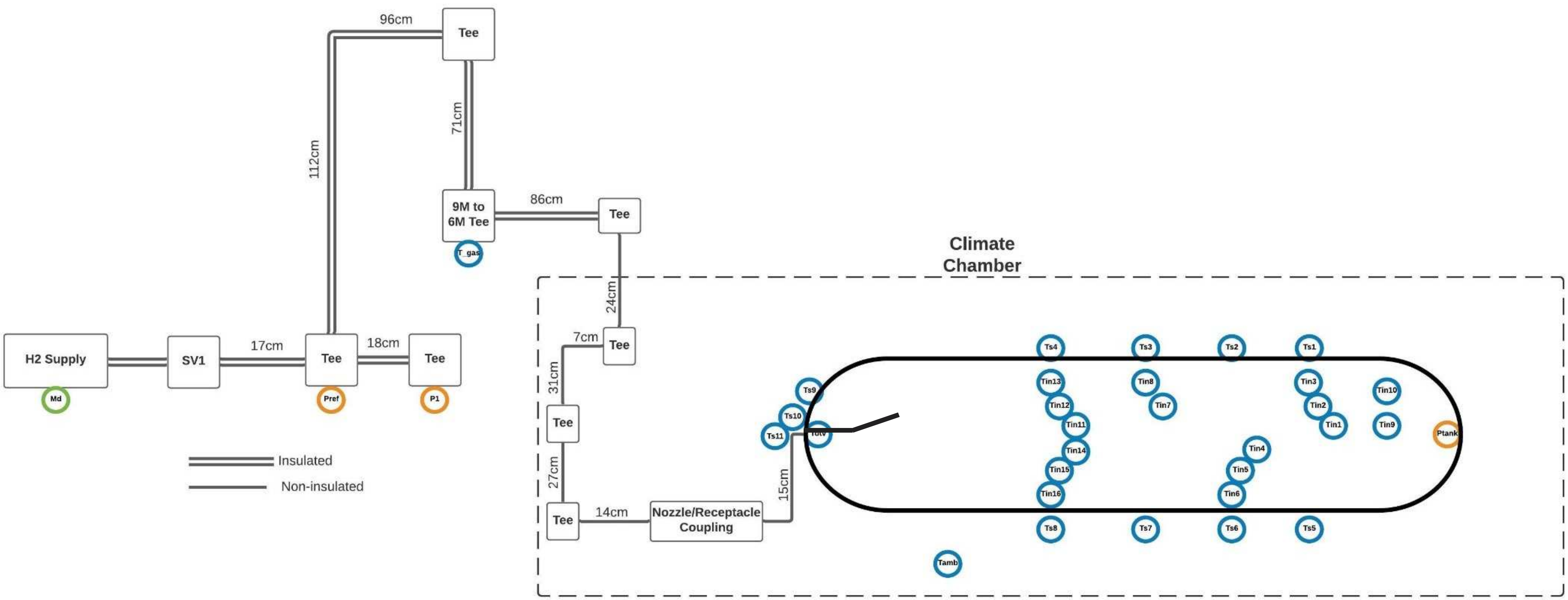
Main differences between SOFIL (Air Liquide) and HyFILL (Engie):

- Pressure drop models
- Equation of state for the estimation of gas properties
- External heat transfer coefficient (fixed in HyFILL and Nusselt correlation for SOFIL)

Outputs
- **Tank gas temperature**
- **Tank gas pressure**
- **Tank wall temperature**
- **Gas injection mass flow rate**
- **etc**

Experimental set-up for Nikola 165L, type 4 and 700 bar tank used for modelling validation

H2 PRHYDE
Protocol for heavy-duty Hydrogen refuelling



Test matrix for Nikola tank

Estimated Date	Test Number	Tank	Initial Pressure (bar) [2]	Ambient / Chamber Temperature (°C) [1]	Dispenser Pre-cooling Temperature (°C) [3]	Dispenser Pre-cooling Tolerance (°C) [3]	Dispenser Pressure Profile	End of fill Criteria
Complete	1	Type 4, H70, 165L	20	15	-40	+7/-0	Constant PRR - 8 MPa/min	97-100% SOC
Complete	2	Type 4, H70, 165L	20	**50**	-40	+7/-0	Constant PRR - 8 MPa/min	97-100% SOC
Complete	3	Type 4, H70, 165L	20	**40**	-40	+7/-0	Constant PRR - 8 MPa/min	97-100% SOC
Complete	4	Type 4, H70, 165L	20	**-30**	-40	+7/-0	Constant PRR - 8 MPa/min	97-100% SOC
Complete	5	Type 4, H70, 165L	20	**-15**	-40	+7/-0	Constant PRR - 8 MPa/min	97-100% SOC
Complete	6	Type 4, H70, 165L	20	**0**	-40	+7/-0	Constant PRR - 8 MPa/min	97-100% SOC
Complete	7	Type 4, H70, 165L	20	15	**-33**	+0/-7	Constant PRR - 8 MPa/min	97-100% SOC
Complete	8	Type 4, H70, 165L	20	15	**-26**	+0/-7	Constant PRR - 8 MPa/min	97-100% SOC
Complete	9	Type 4, H70, 165L	20	15	**-17.5**	+0/-7	Constant PRR - 8 MPa/min	97-100% SOC
Complete	10	Type 4, H70, 165L	**50**	15	-40	+7/-0	Constant PRR - 8 MPa/min	97-100% SOC
Complete	11	Type 4, H70, 165L	**250**	15	-40	+7/-0	Constant PRR - 8 MPa/min	97-100% SOC
Complete	12	Type 4, H70, 165L	20	15	-40	+7/-0	**Constant PRR - 5 MPa/min**	97-100% SOC
Complete	13	Type 4, H70, 165L	20	15	-40	+7/-0	**Constant PRR - 16 MPa/min**	97-100% SOC
Complete	14	Type 4, H70, 165L	20	15	-40	+7/-0	**Constant PRR - 20 MPa/min**	97-100% SOC
Complete	15	Type 4, H70, 165L	20	15	-40	+7/-0	**20 MPA/min for 3.85 min, transition to 1MPA/min**	97-100% SOC
Complete	16	Type 4, H70, 165L	20	15	-40	+7/-0	**20 MPA/min for 3.85 min, transition to 3MPA/min**	97-100% SOC
Complete	17	Type 4, H70, 165L	20	15	-40	+7/-0	**20 MPA/min for 3.33 min, transition to 1 MPA/min with pulse of 8 MPA/min for 10s every 30s**	97-100% SOC
Complete	18	Type 4, H70, 165L	20	**40**	**-17.5**	+0/-7	Constant PRR - 8 MPa/min	97-100% SOC

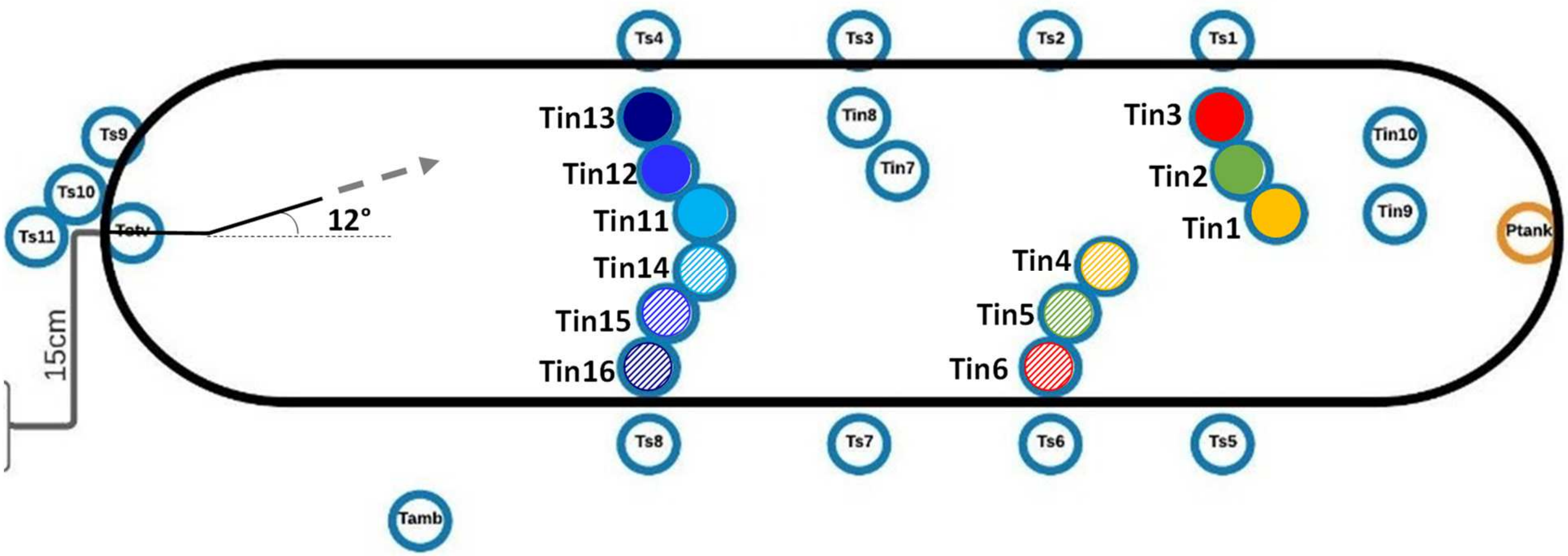
Notes:

1 Vessel is soaked to ambient/chamber temperature with a +2/-2°C tolerance at the start of each test

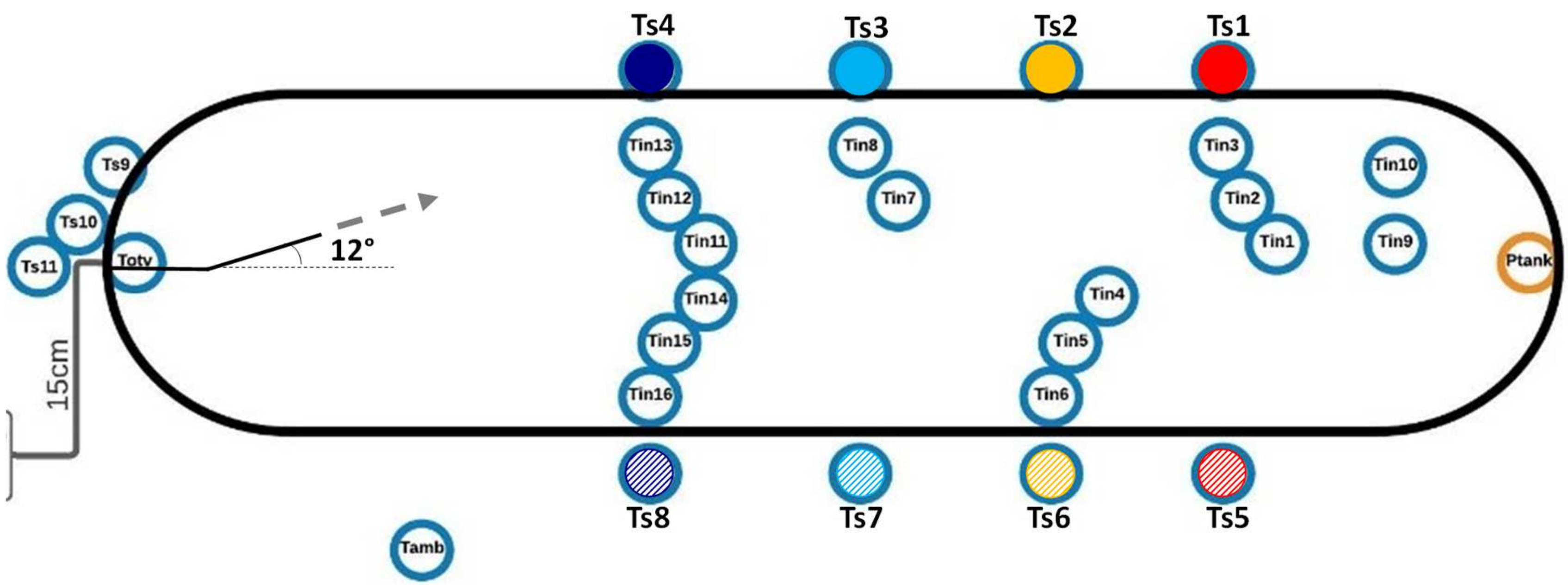
2 Initial pressure tolerance is +1/-1 bar

3 Dispenser pre-cooling temperature represents a stabilized target. Acceptable tolerance for each target is the standard pre-cooling range; T20 (-17.5C to -26C), T30 (-26C to -33C), T40 (-33C to -40C)

Color codes for internal thermocouples (thermocouple tree)



Color codes for external thermocouples



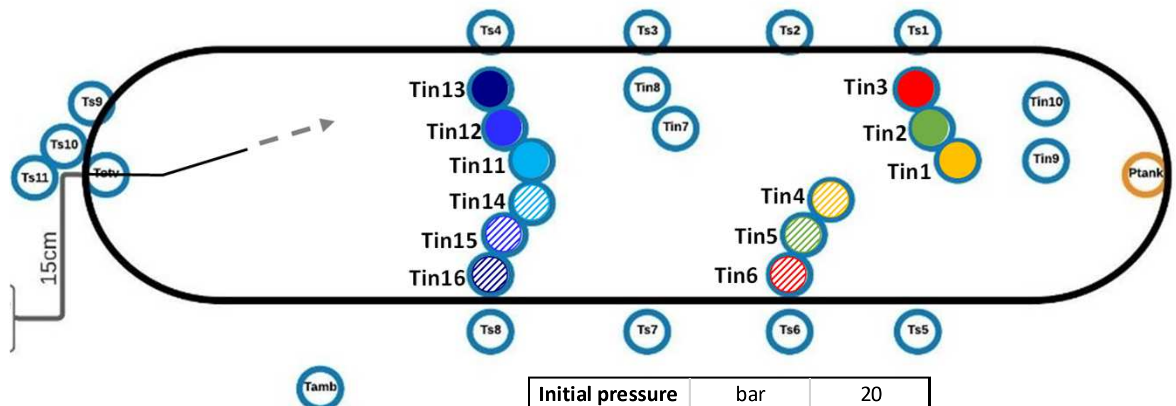
Determination of piping characteristics: kv and m*Cp

- kv is better determined based on the test with the highest flow : test #14 => kv = 0.13 m^3/h

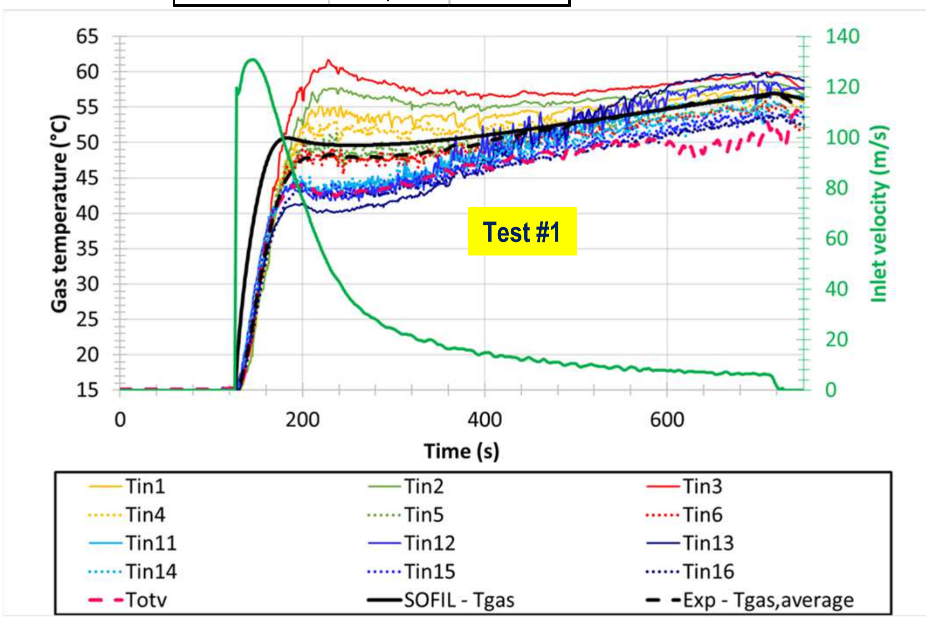
- m*Cp (thermal inertia) piping is better estimated from the test with the highest ambient temperature: test #2

  => m*Cp = 5140 J/K

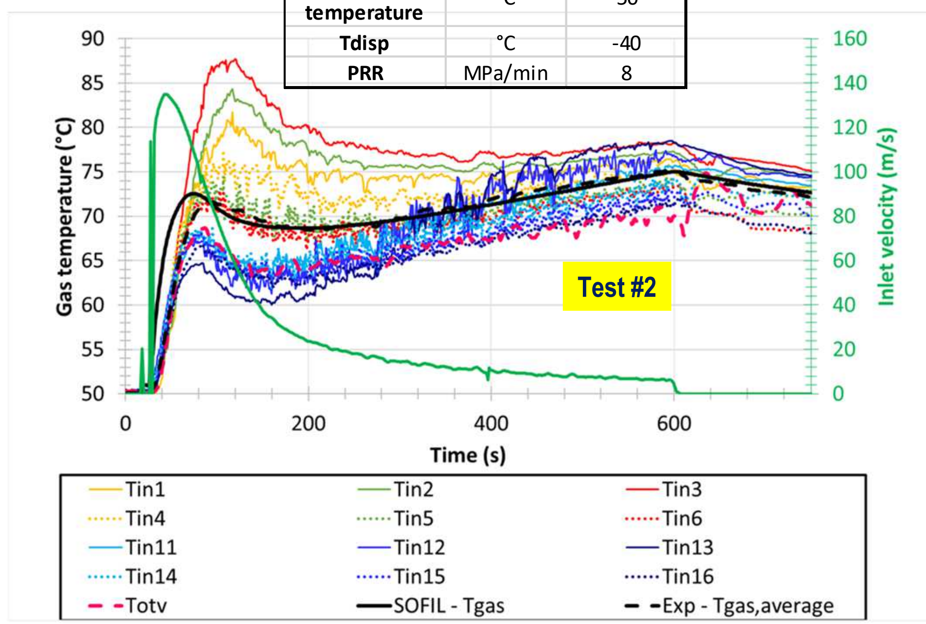
Test #1 and 2 results



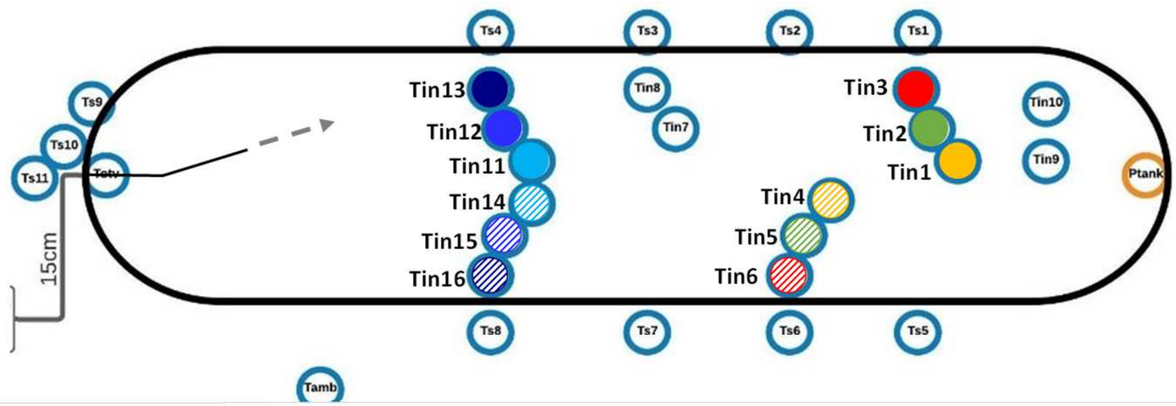
Initial pressure	bar	20
Ambient temperature	°C	15
Tdisp	°C	-40
PRR	MPa/min	8

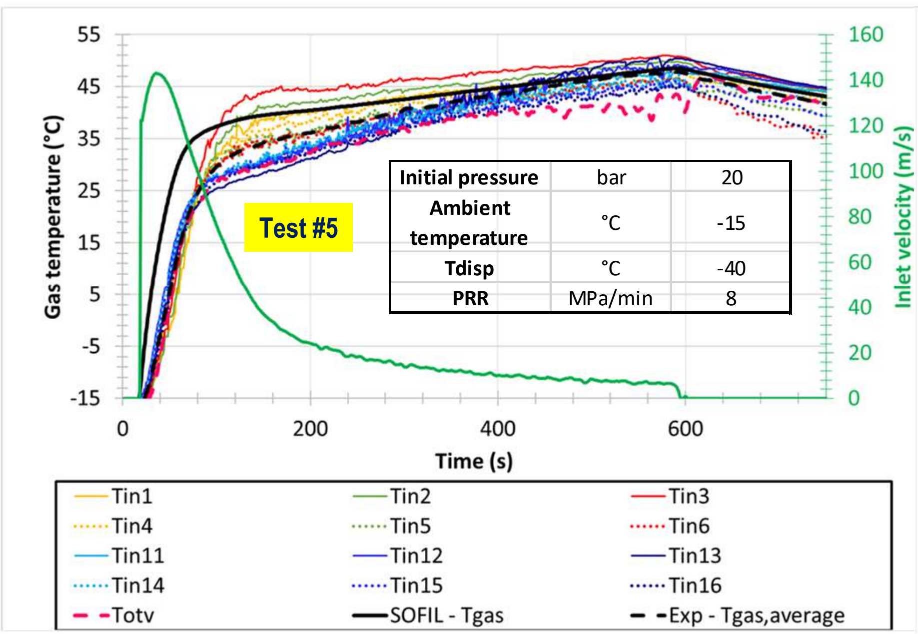


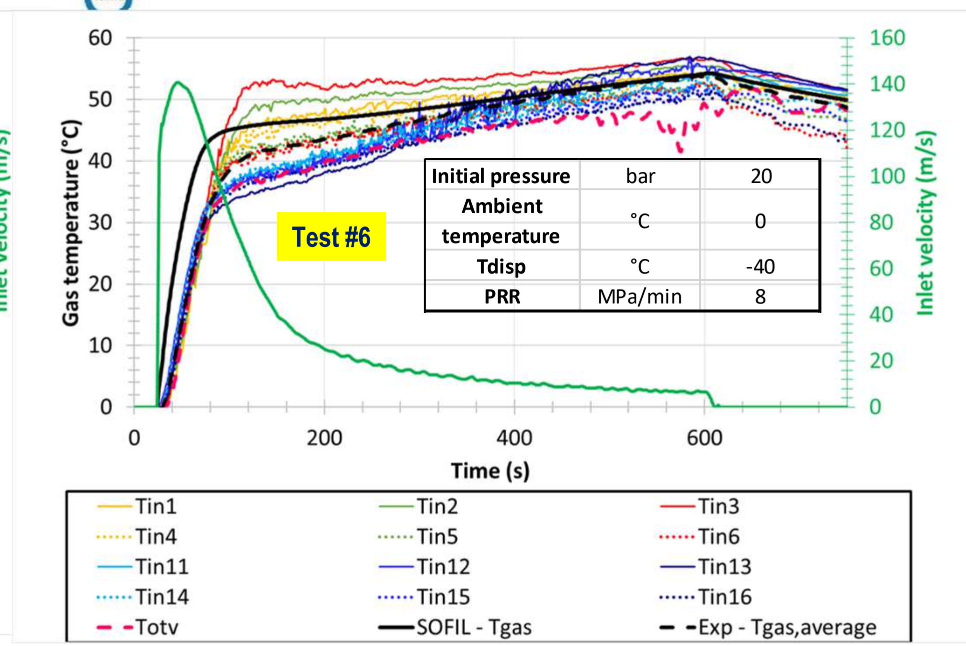
Initial pressure	bar	20
Ambient temperature	°C	50
Tdisp	°C	-40
PRR	MPa/min	8



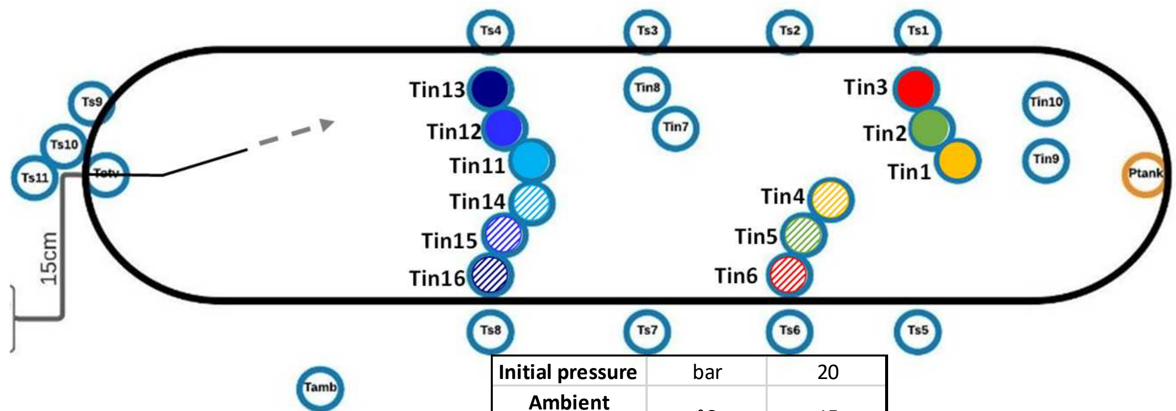
Test #5 and 6 results



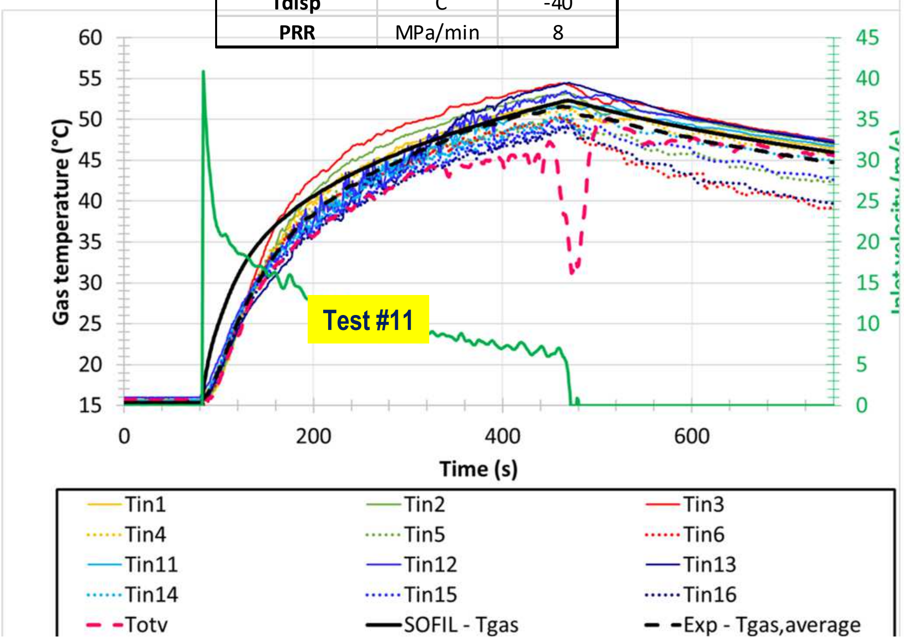




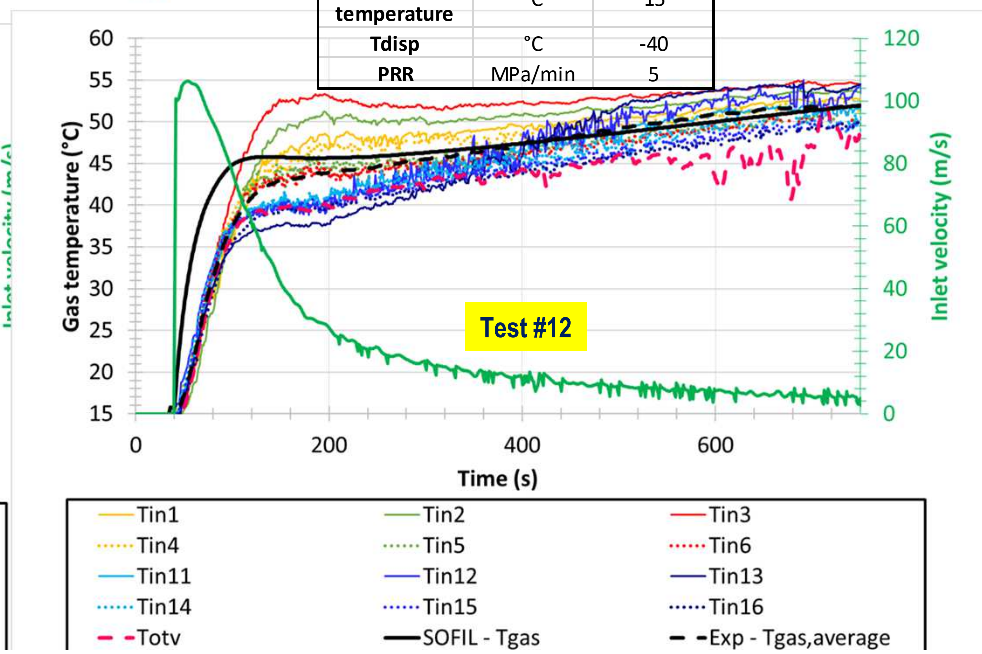
Test #11 and 12 results



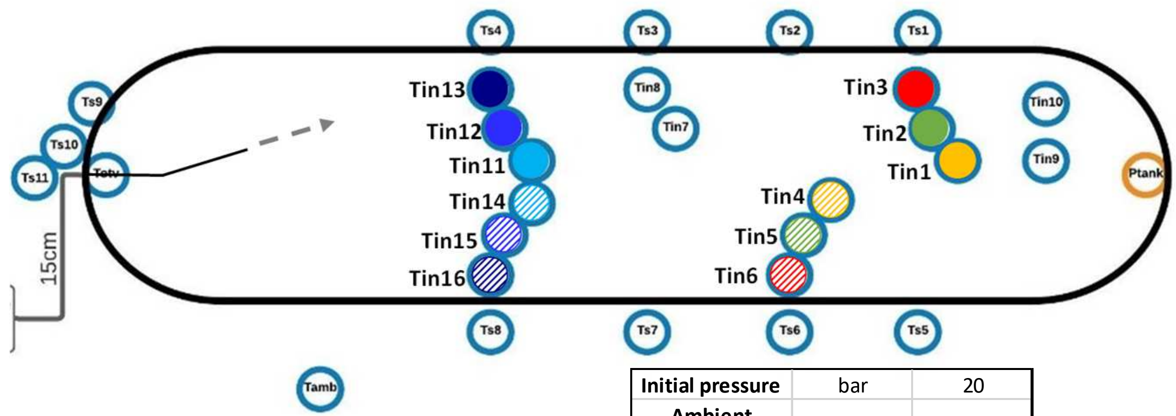
Initial pressure	bar	250
Ambient temperature	°C	15
Tdisp	°C	-40
PRR	MPa/min	8



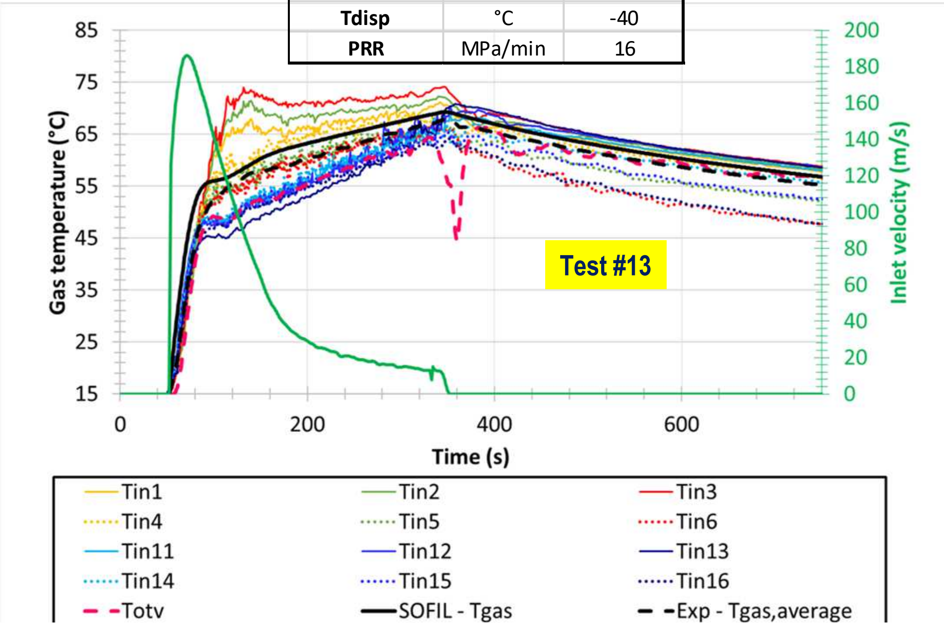
Initial pressure	bar	20
Ambient temperature	°C	15
Tdisp	°C	-40
PRR	MPa/min	5



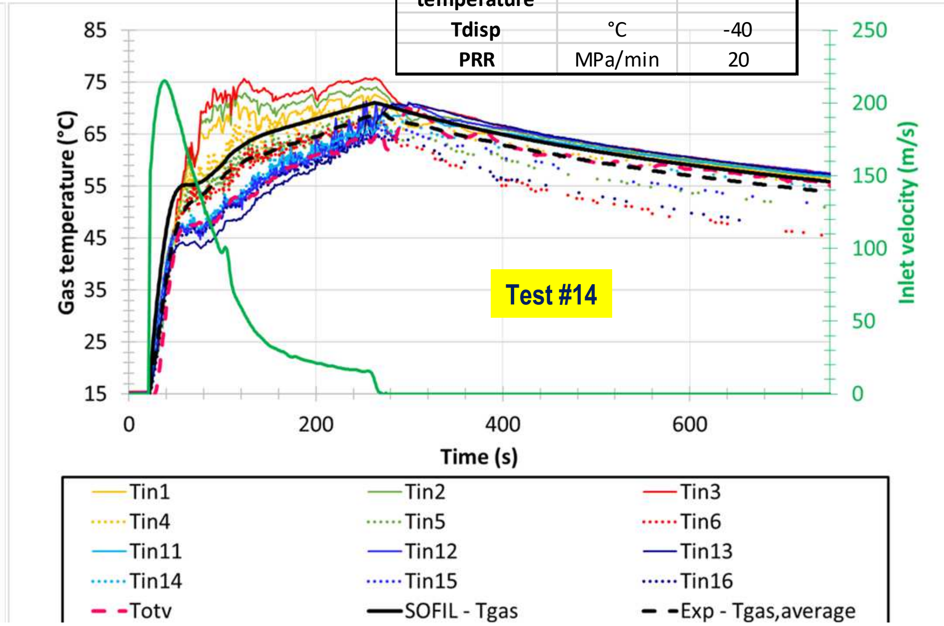
Test #13 and 14 results



Initial pressure	bar	20
Ambient temperature	°C	15
Tdisp	°C	-40
PRR	MPa/min	16

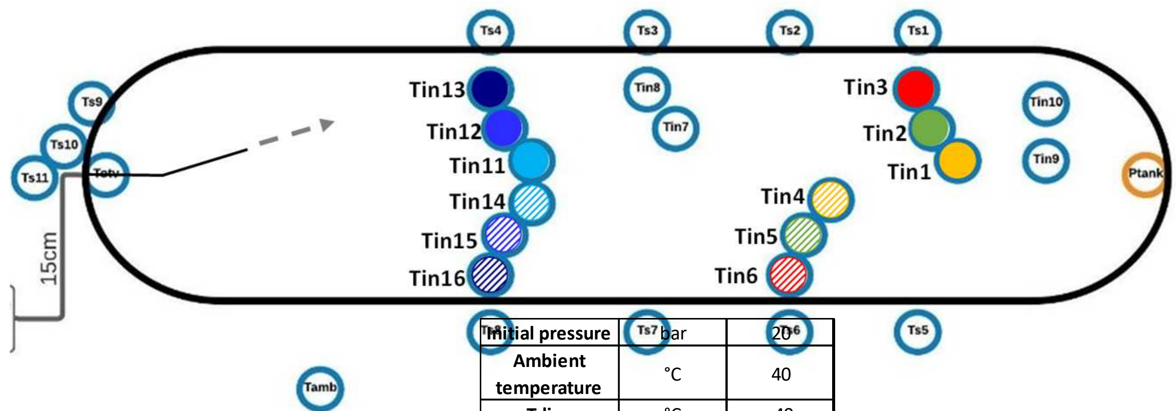


Initial pressure	bar	20
Ambient temperature	°C	15
Tdisp	°C	-40
PRR	MPa/min	20

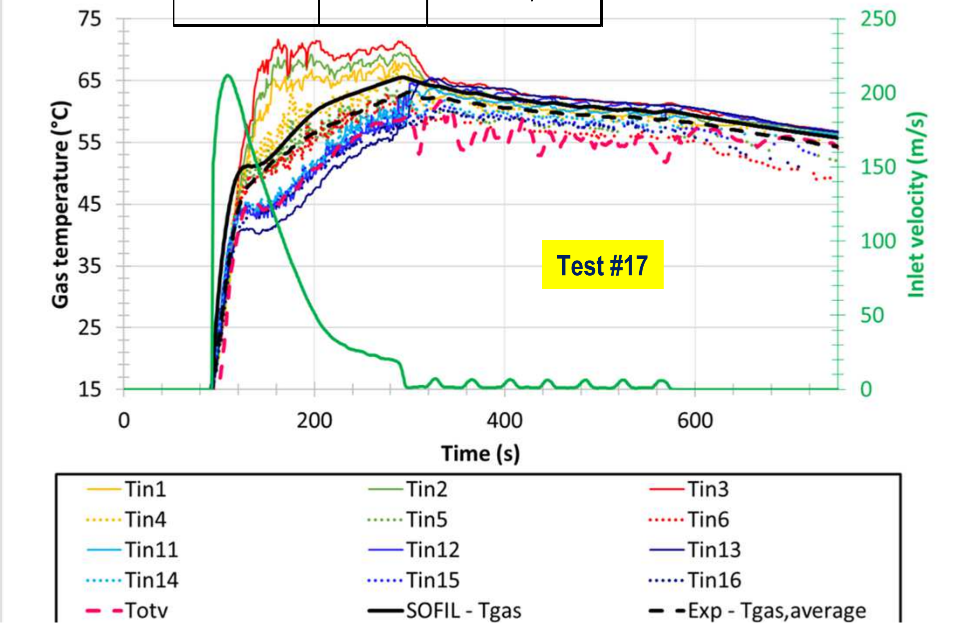


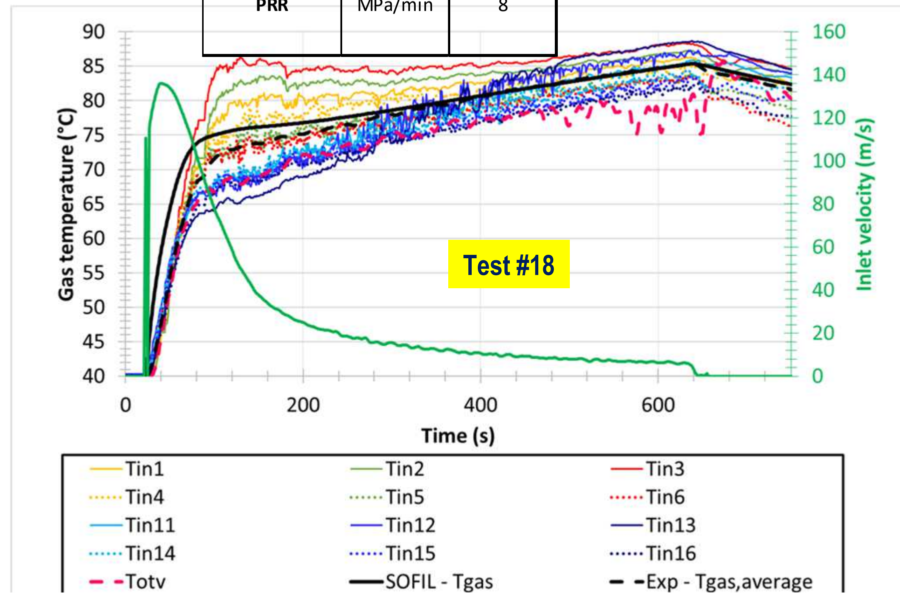
Test #17 and 18 results

Initial pressure	bar	20
Ambient temperature	°C	15
Tdisp	°C	-40
PRR	MPa/min	20MPa/min for 3.33min, transition to 1MPa/min with pulse of 8MPa/min for 10s every 1min

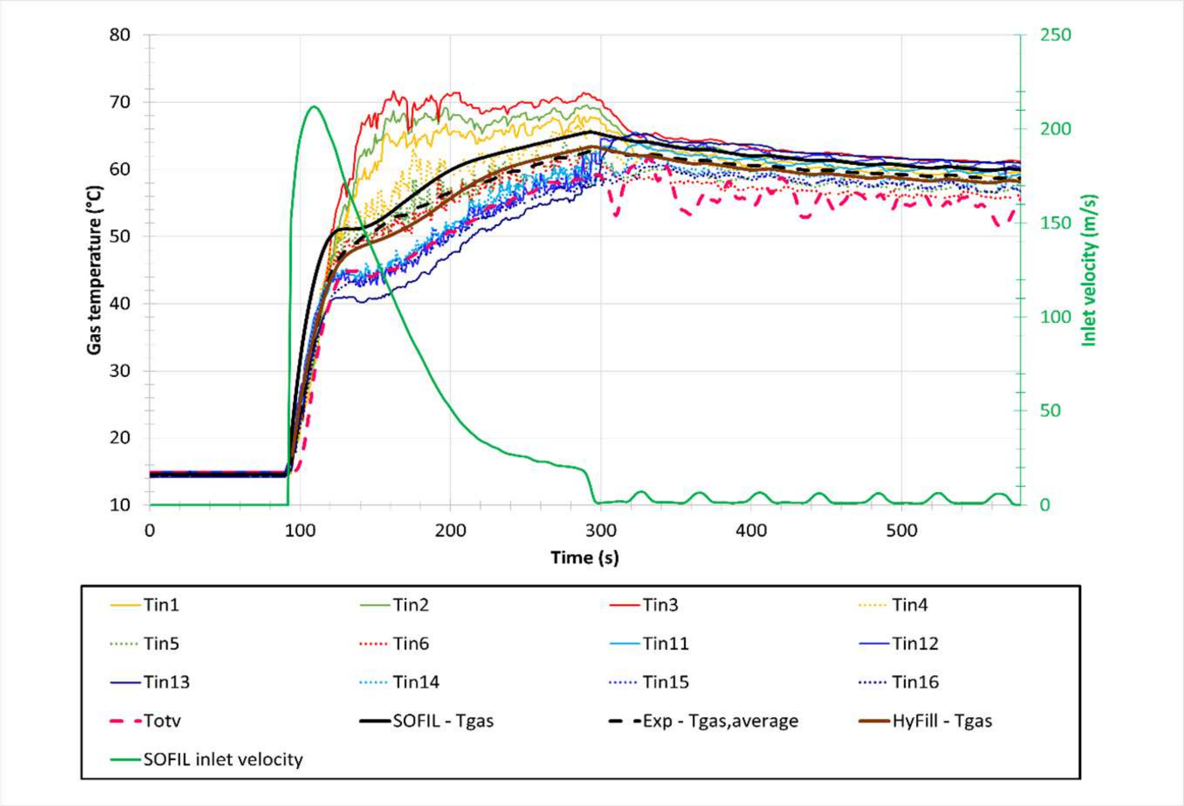


Initial pressure	bar	20
Ambient temperature	°C	40
Tdisp	°C	-40
PRR	MPa/min	8





Comparison of SOFIL and HyFILL model prediction with experiment data for test #17



Conclusions (1/2)

- SOFIL (Air Liquide) simulations were conducted for 18 refueling tests of Nikola 165L type 4 tank. The same for HyFILL (Engie).
- Determination of kv between the dispenser and the tank: kv = 0.13 m^3/h
- Determination of the heat capacity for the filling line: m*Cp = 5140 J/K
- A delay should be considered between the thermocouples and the gas temperature inside the tank (mostly visible at the filling first part when the gas temperature is varying a lot). This delay is due to the response time of the convection around the thermocouple extremity and also to the heat conduction in the thermocouple thickness. The more the filling flow is important, the less the delay will be.
- SOFIL modeling results agree well (2 to 3°C of difference) with the spatial average gas temperature inside the tank for all the 18 tests. The same for HyFILL.
- Gas temperature gradients inside the tank are more observed horizontally at the filling first half and less vertically at the filling end. **The temperature gradient could reach 27°C between the hottest thermocouple and the coldest one on the thermocouple tree**.

Conclusions (2/2)

- **In average, OTV temperature is less by 7°C** than the average gas temperature measured by thermocouple tree during the filling phase
- **Local gas temperature exceeds 85°C in test #2** even when average gas temperature is around 70°C
- To understand temperature gradient occurrence, CFD calculations were launched in 2 cases:
  - **test #2** where temperature gradients are important
  - **test #14** where the flow is high
- CFD results will be presented in another paper in this conference (**# 260**)

Thank you for your attention