Towards development of a tool to simulate hydrogen tank fuelling

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Developing fuelling modelling tool

Benefits and applicability range

Benefits:

- Fast
- Inexpensive
- Tank independent

Applicability range based on J2601 (but not limited to):

- Temperature inside: -40 ^{0}C$\leq T_{gas} \leq$85 ^{0}C
- Pressure: 0.5 MPa$\leq P_{gas} \leq$1.25×NWP
- SOC: not to exceed 100%
- Filling time: 3-5 min

Note: state of charge (SOC) = $\rho(P,T)/\rho(NWP,15^0C)$

Fuelling

J2601

Fuelling protocol for light duty gaseous hydrogen surface vehicles J2601:

- Two approaches:
  - Look-up table: utilising a fixed pressure ramp
  - Formula based: utilising a dynamic pressure ramp
- Currently J2601 protocol is designed for:
  - Delivery temperature categories: -40^{0}C, -30^{0}C, -20^{0}C
  - Pressure classes: 35 MPa and 70 MPa
  - Compressed hydrogen storage: 49.7 L to 248.6 L
- Future development (J2601):
  - Warmer fuel delivery temperatures (-10^{0}C or ambient)
  - Smaller compressed hydrogen storage sizes

The model

Formulation

Formulation		
Filling model	**Equation**	**Reference**
Gas	▪ Form of energy conservation equation ▪ Real gas EOS (Abel-Noble)	Molkov et al., 2009 Johnson, 2005
Tank	▪ Unsteady heat transfer equation ▪ Nu correlations for convective for inside heat transfer ▪ Constant heat transfer coefficient on external wall ▪ Original approach based on the entrainment theory	Patankar, 1980 Woodfield, 2008 Ricou & Spalding, 1961
Input	▪ Tank properties: volume; internal surface, diameter and length; external diameter; load-bearing wall and liner thicknesses and their material thermal properties (thermal conductivity, specific heat capacity, density); external heat transfer coefficient; nozzle diameter; initial temperature ▪ Hydrogen properties: co-volume constant; specific heat capacity; thermal conductivity; specific gas constant; dynamic viscosity; initial pressure and temperature; pressure ramp ▪ Other inputs: ambient temperature; air viscosity; fuelling time	
Output	▪ Gas temperature inside the tank ▪ Temperature profile within the tank wall and liner ▪ Gas density or SOC	

Validation

Type IV tank, 29 L

Test (Miguel et al., 2016):

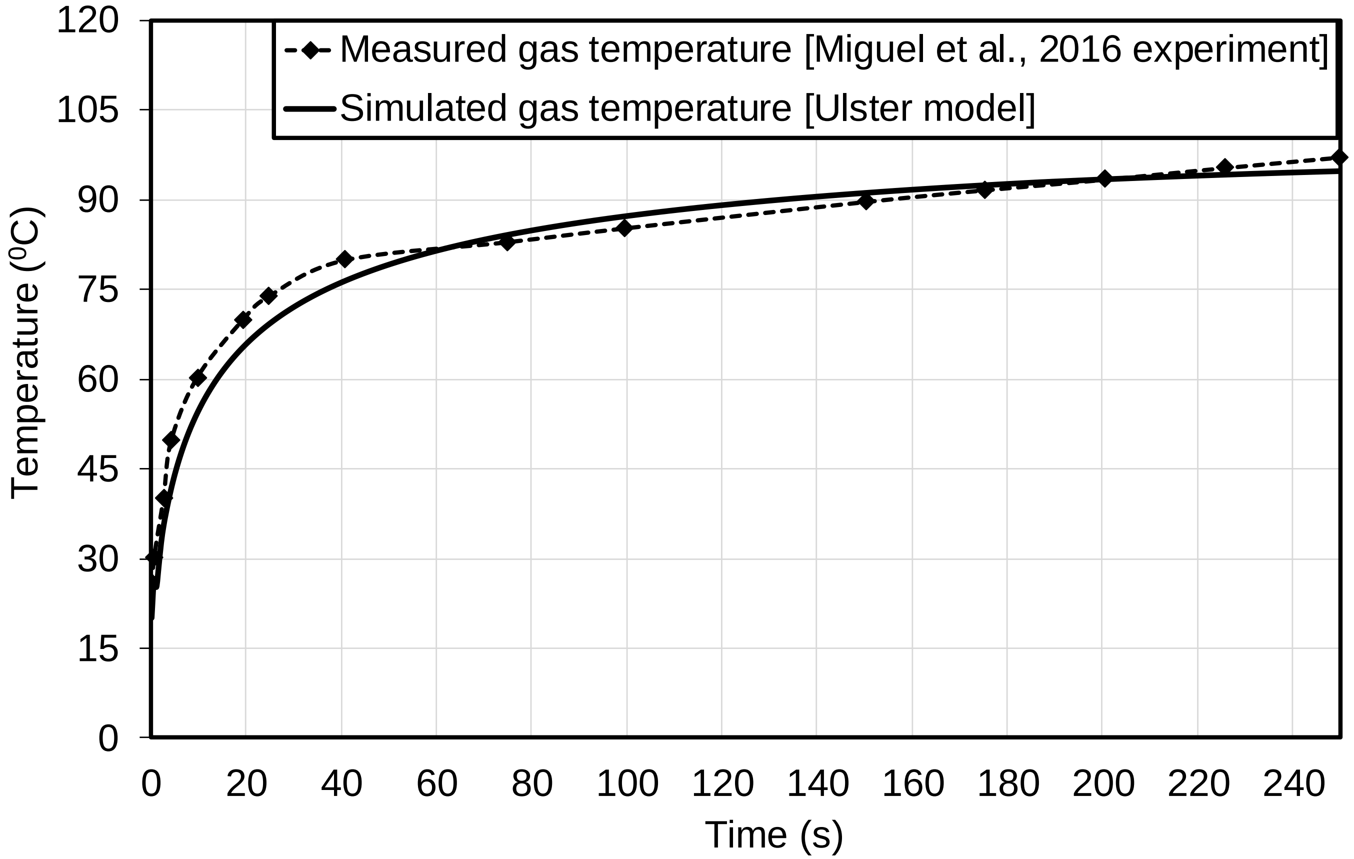
- Initial pressure 2 MPa; target pressure 77 MPa
- 3 mm orifice

Tank properties (Acosta et al., 2014):

- Volume 29 L (external length 827 mm; external diameter 279 mm; internal diameter 230 mm)
- CFRP: thermal conductivity 0.74 W m^{-1} K^{-1}; specific heat capacity 1120 J kg^{-1} K^{-1}; density 1494 kg m^{-3}
- HDPE liner: thermal conductivity 0.385 W m^{-1} K^{-1}; specific heat capacity 1580 J kg^{-1} K^{-1}; density 945 kg m^{-3}

Validation results

Type IV tank, 29 L



Maximum experimental temperature difference in the tank is 3^0C (Cebolla et al., 2014). The model gives maximum deviation 5^0C.

Validation

Type III tank, 40 L

Test (Miguel et al., 2016):

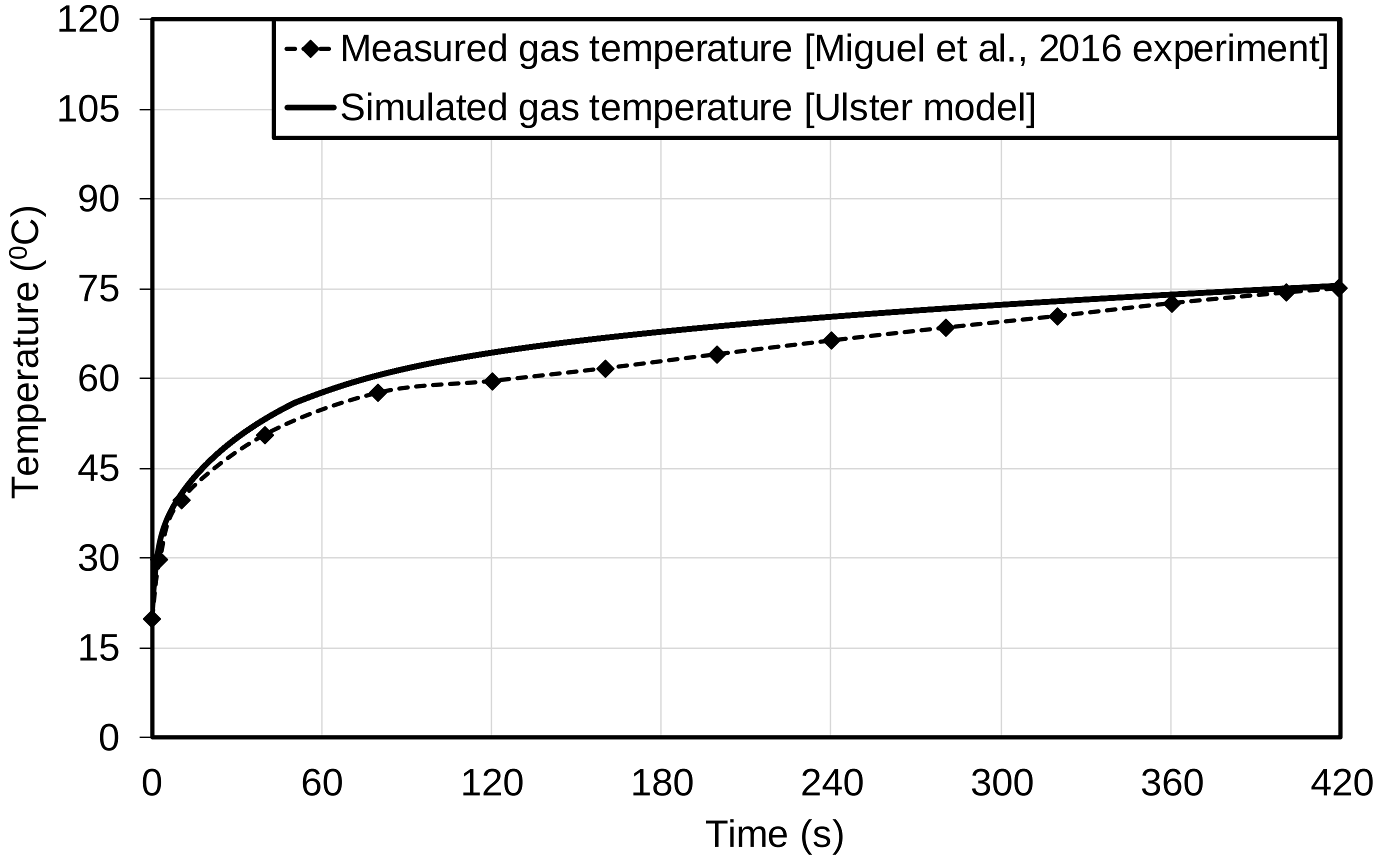
- Initial pressure 2 MPa; target pressure 77 MPa
- 3 mm orifice

Tank properties (Acosta et al., 2014):

- Volume 40 L (external length 920 mm; external diameter 329 mm; internal diameter 290 mm)
- CFRP: thermal conductivity 0.74 W m^{-1} K^{-1}; specific heat capacity 1120 J kg^{-1} K^{-1}; density 1494 kg m^{-3}
- Aluminium liner: thermal conductivity 167 W m^{-1} K^{-1}; specific heat capacity 900 J kg^{-1} K^{-1}; density 2700 kg m^{-3}

Validation result

Type III tank, 40 L



Maximum experimental temperature difference in the tank is 3^0C (Cebolla et al., 2014). The model gives maximum deviation 5^0C.

Validation

Type III tank, 74 L

Test (Zheng et al., 2013):

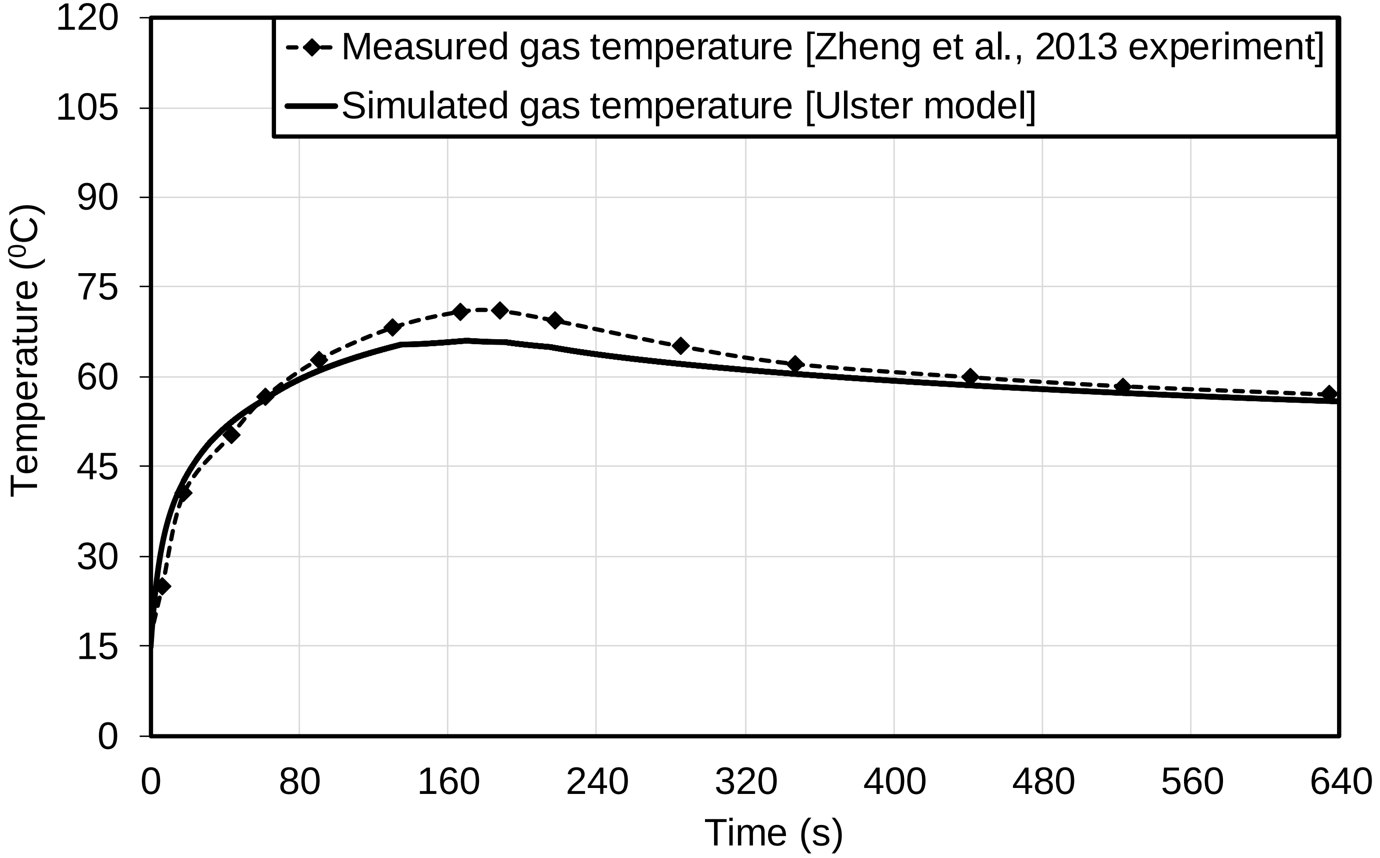
- Initial pressure 5.5 MPa; target pressure 70 MPa
- 5 mm orifice

Tank material properties (Zheng et al., 2013)

- Volume 74 L (external length 1030 mm; external diameter 427 mm; internal diameter 354 mm)
- CFRP: thermal conductivity 0.612 W m^{-1} K^{-1}; specific heat capacity 840 J kg^{-1} K^{-1}; density 1570 kg m^{-3}
- Aluminium liner: thermal conductivity 238 W m^{-1} K^{-1}; specific heat capacity 902 J kg^{-1} K^{-1}; density 2700 kg m^{-3}

Validation result

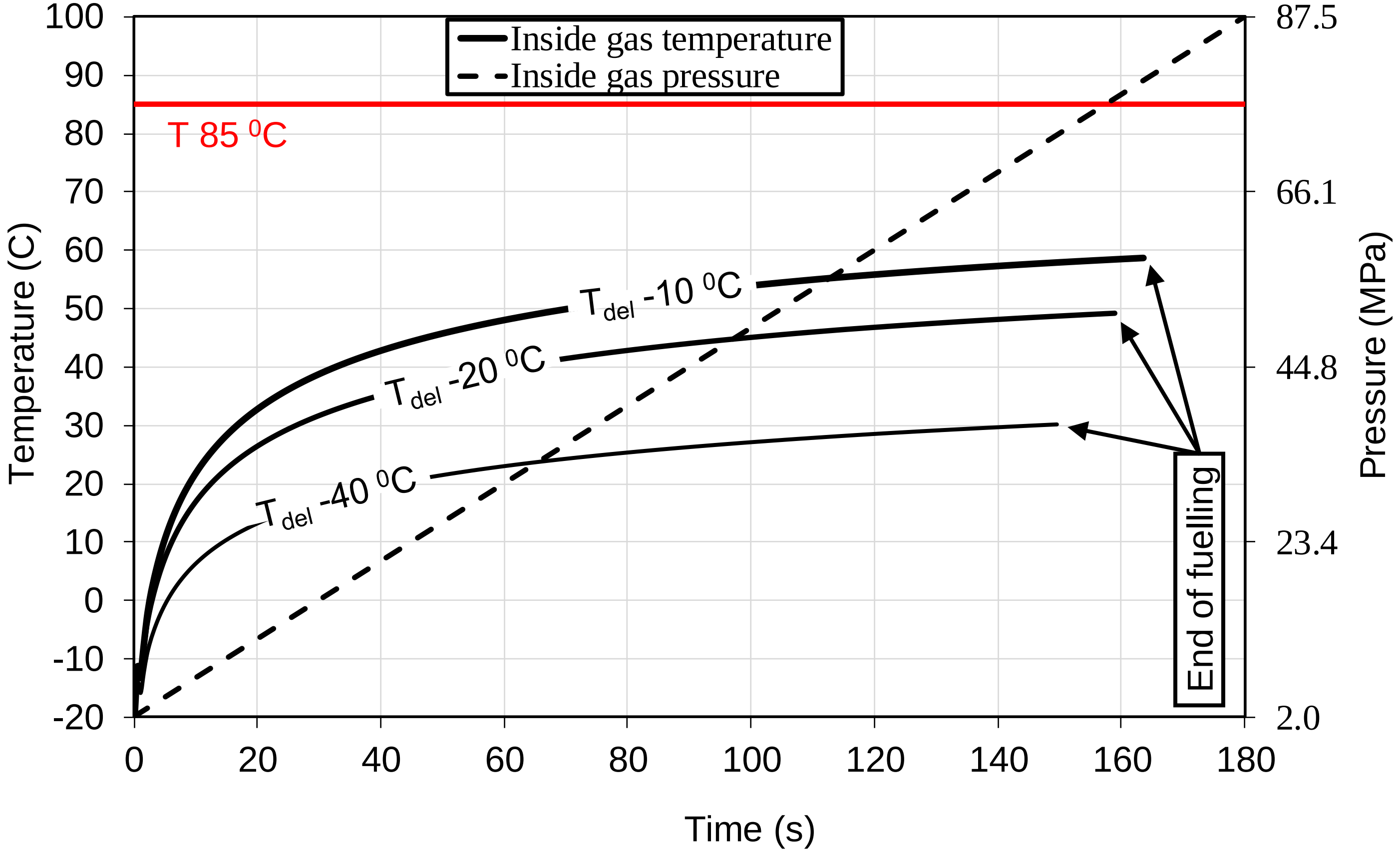
Type III tank, 74 L



Maximum experimental temperature difference in the tank is 5^{0}C (Zheng et al., 2013). The model gives the same maximum deviation 5^{0}C.

Model application: Type IV tank, 50 L

Ambient temperature T_{amb} = -20^{0}C

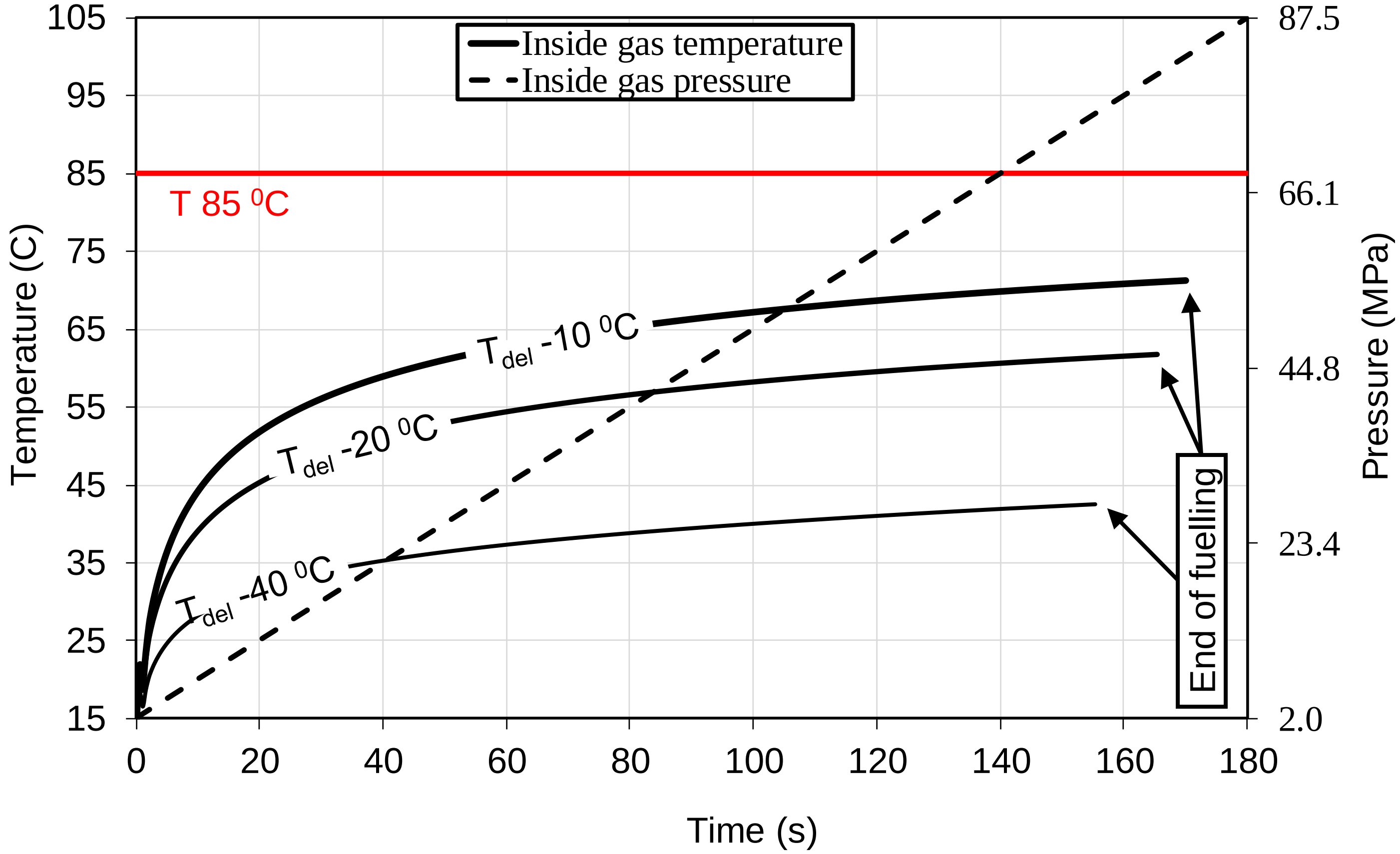


End of fuelling is at SOC 100%.

No pipe with heat losses in simulations (assuming double wall vacuumed hose)

Model application: Type IV tank, 50 L

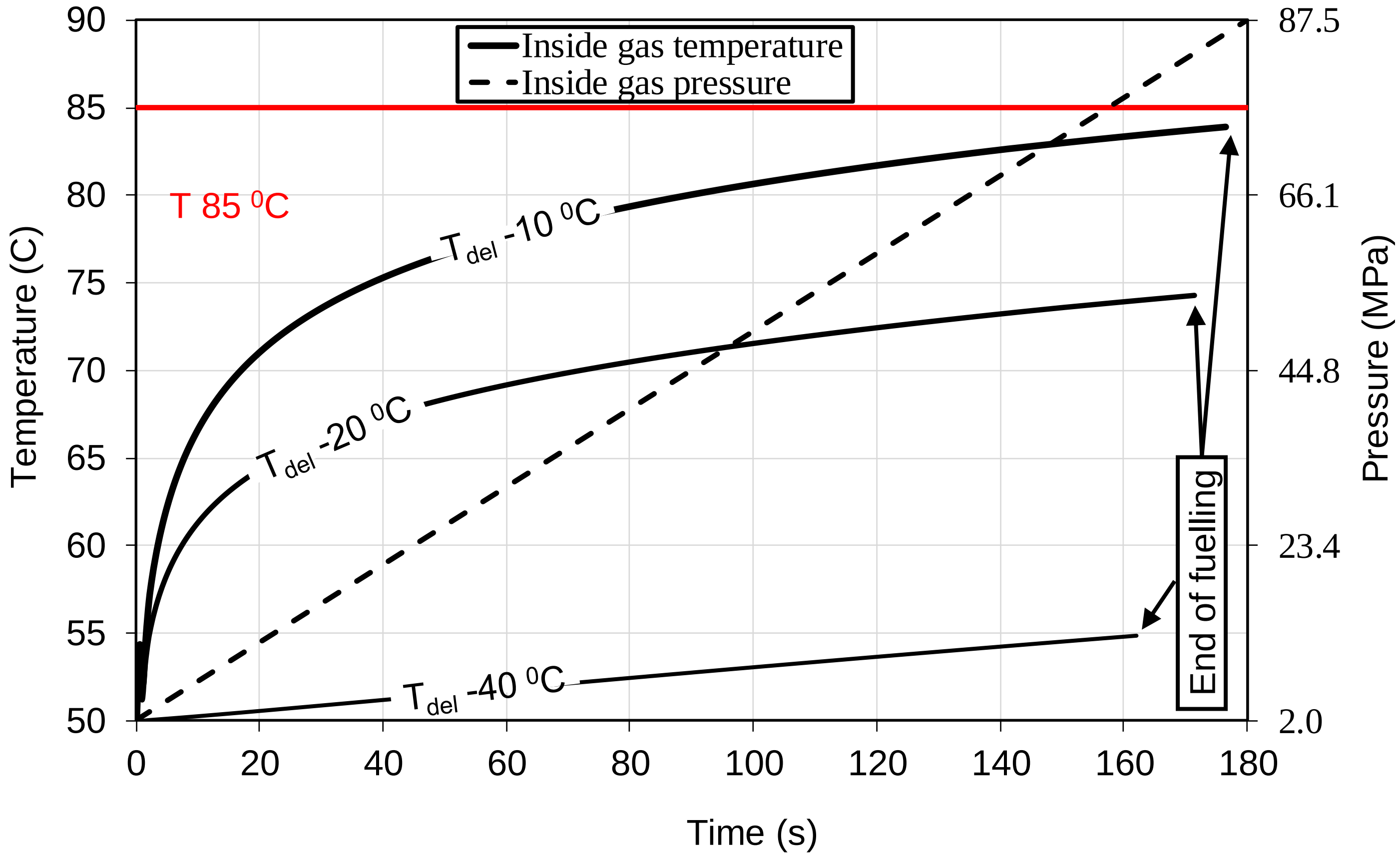
Ambient temperature $T_{amb} = 15^0C$



End of fuelling is at SOC 100%

Model application: Type IV tank, 50 L

Ambient temperature T_{amb} = 50^0C

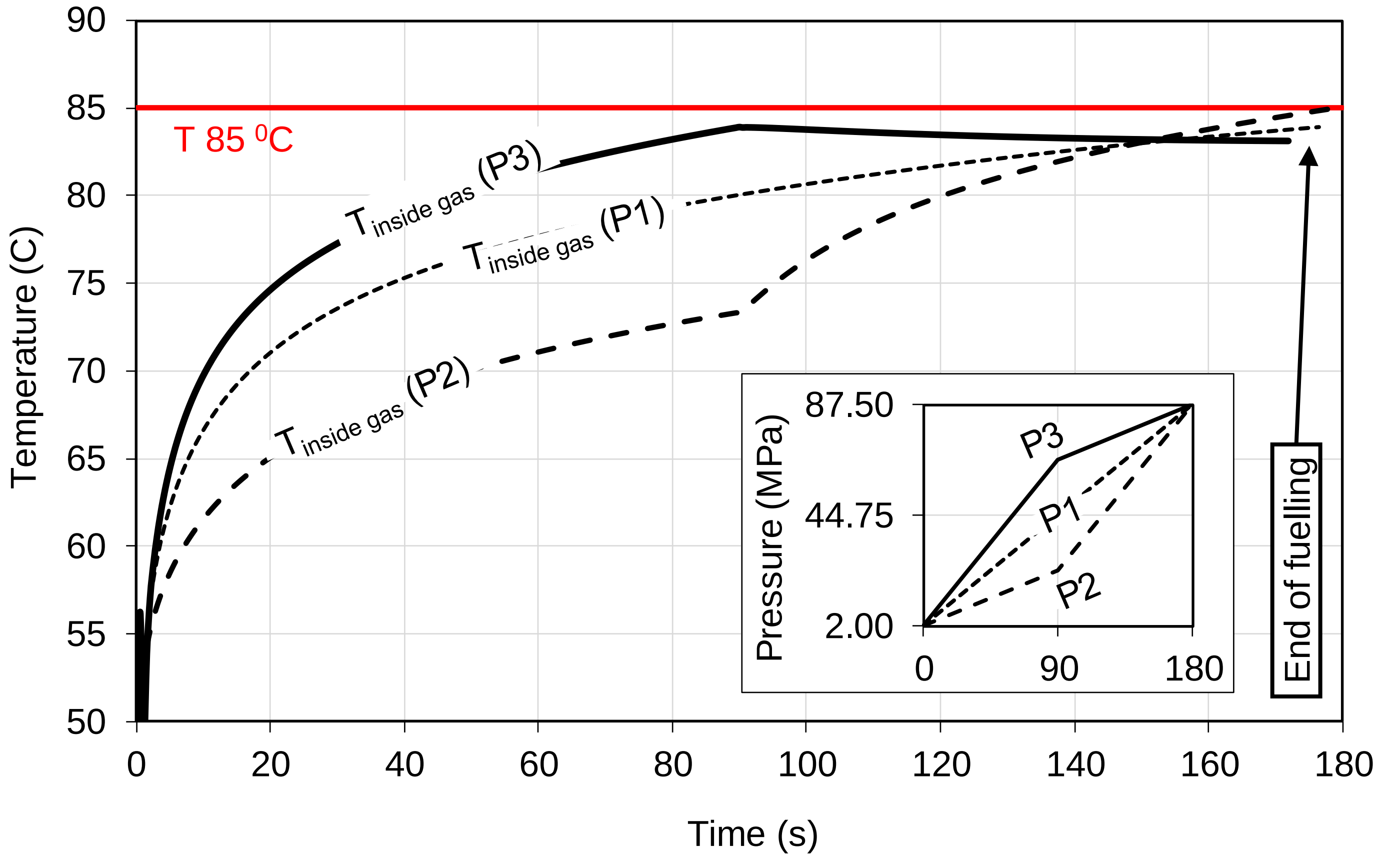


End of fuelling is at SOC 100%.

J2601: fuelling at T_{amb}=50 C with T_{del}=-40 C from 2 to 77.8 MPa takes with ramp 3.2 MPa/min (77.8-2)/3.2=24 min?! Fuelling with “adiabatic” hose gives only 2 min 45 s!

Model application: Type IV tank, 50 L

Effect of pressure ramp: T_{amb} 50^{0}C; T_{del} -10^{0}C

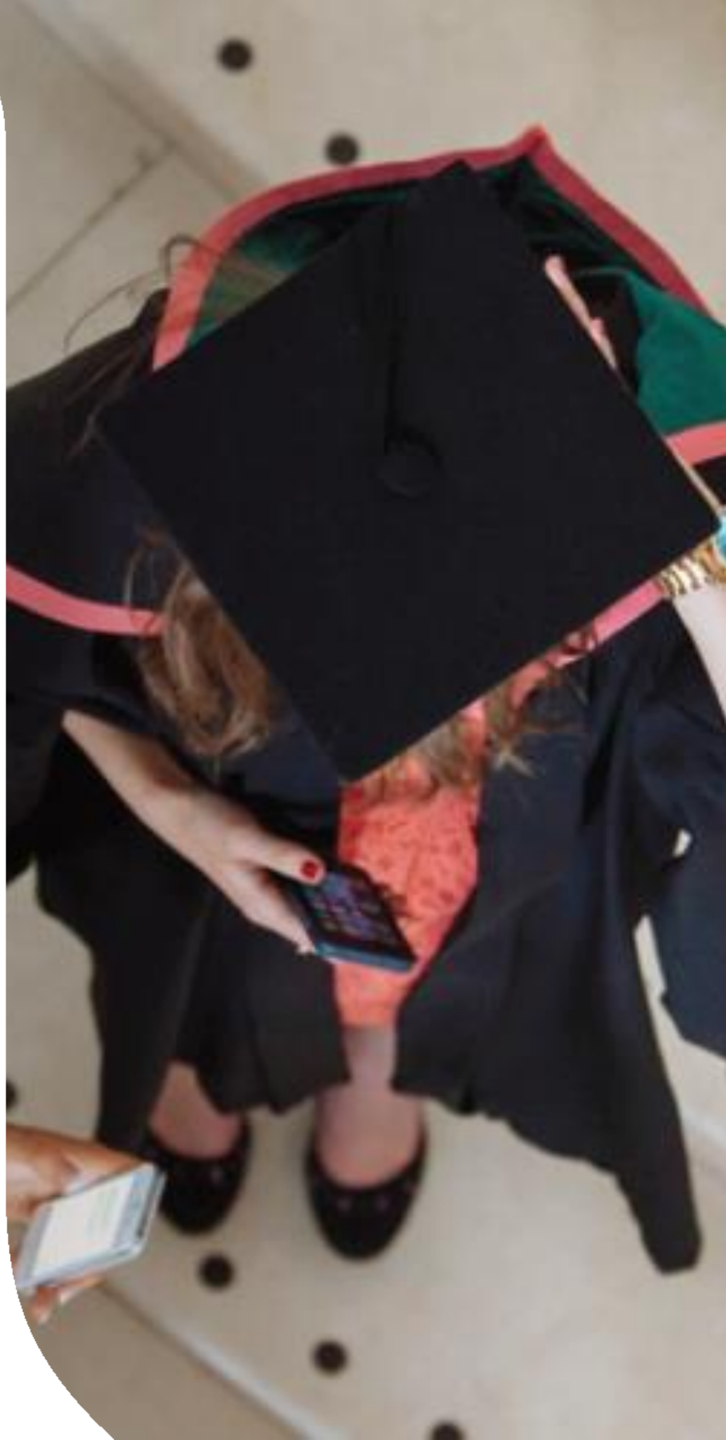


End of fuelling is at SOC 100%

Concluding remarks

- The model for simulating hydrogen tank fuelling is formulated and validated against tests with Type III and Type IV tank fuelling.
- The model predictions are “instantaneous” with predictive accuracy within $\pm 5^0 C$.
- The model could be used to design efficient fuelling protocols and fuelling control systems.
- The “adiabatic” hose fuelling efficiency should be further tested experimentally.

THANK YOU



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