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HYFILL: HEAVY-DUTY HYDROGEN VEHICLES REFUELLING STATION MODELLING TOOL. DESCRIPTION AND VALIDATION.

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ABSTRACT

The heavy-duty transport sector is responsible for 25% of greenhouse gas emission from road transport and for 6% of total EU GHGs emissions. The EU Commission aim to reduce these emissions of 90% by 2040 (European Commission, 2024). Heavy -duty hydrogen fuel-cell vehicles (HD-FCEV) have the potential to reduce it. To develop the heavy hydrogen mobility sector, it is necessary to decrease the hydrogen cost at the dispenser and to ensure a safe and fast refuelling. Hence, hydrogen refuelling station (HRS) designs should guarantee performances in terms of rapidity and safety of the fillings, while remaining economically attractive. To achieve this goals, modelling HRS can allow to evaluate innovative designs or develop new refuelling protocols. This enables to support the realisation of innovative projects, as it allows to understand the thermodynamic behaviour of the station components and their interactions (Genovese et al., 2023).

This is why ENGIE Lab CRIGEN developed in collaboration with IMT Mines Albi a HRS modelling tool named HyFill. It includes all the main components of a HRS: high-pressure cascade storage system, pressure-control valve, heat-exchanger, pre-cooling system, fuelling line, vehicle storage system (Rothuizen, 2013). This work presents the development of HyFill and focuses on the choices made to model the components. To predict with precision and low computational cost the thermodynamic behaviour of the station components, the model is built with a lump approach. Each component model is based on energy balance, mass balance and thermodynamic properties of hydrogen (H₂) (Kunz and Wagner, 2012). For certain components, the use of empirical correlations is necessary for modelling. These correlations are either taken from the literature or supplied by the manufacturers. At the core of the HyFill tool is the tank model, which describes the gas thermodynamic behaviour during refuelling and defueling. The model considers the effect of tank geometry and material properties to model the heat transfer between gas, tank wall, and ambient. Validation work was conducted with experimental data from filling and defueling of several different tanks in various working conditions. HyFill can predict the final gas temperature with a precision of ± 3 K.

HyFill can be used to simulate the refuelling of a HD-FCEV, predict the performances of a given station, and test refuelling protocols. In perspective, the development of HyFill could enable the simulation of consecutive refuelling of vehicles, the prediction of the station performance on back-to-back refuelling and more complex scenarios. The final objective is to define a new methodology to conceive optimal design for heavy-duty HRS.

Keywords: Thermodynamic Modelling, Hydrogen Refuelling Station, Heavy-Duty Hydrogen Mobility

1 INTRODUCTION

The European commission estimates that heavy-duty vehicles (HDVs) are responsible for more than 25% of greenhouse gas (GHG) emissions from road transport, which correspond to 6% of total GHG. To reach carbon neutrality by 2050, the European Commission has introduced a new regulation to guide investments in innovative zero-emission technologies, including hydrogen fuel cell vehicles (FCEVs), and boost the rollout of recharging and refuelling infrastructure (European Commission, 2024). To achieve the development of the refuelling infrastructure it is necessary to improve the efficiency of the HRS technologically and economically. To accelerate and ameliorate the design process of an HRS, the use of simulation tools and in house software can be a great advantage. This allows to reduce the time and resources dedicated to tests, giving insights on the refuelling process and the behaviour of the HRS.

Numerous models have been developed to study the evolution of gas temperature inside vehicle tanks, as it is a key factor limiting refuelling speed. These studies often focus on the onboard tank or the fuelling line and tank. Many studies (Bourgeois et al., 2015; de Miguel et al., 2016; Galassi et al., 2012; Ramasamy and Richardson, 2020) use Computational Fluid Dynamics (CFD) to precisely predict pressure and temperature distribution within the tank. This allows for the investigation of geometrical parameters, such as tank length, diameter, and injector shape, on refuelling performance. Notably, Ebne-Abbasi et al. (2024) successfully modelled and simulated the refuelling process from the cascade to the vehicle tanks using CFD.

Many researchers use 0-dimensional models to study the impact of refuelling parameters such as injection pressure, temperature, ambient conditions, and initial pressure. Studies (Ammouri et al., 2023; Bourgeois et al., 2015; Elgowainy et al., 2017a; Khan et al., 2021; Rasmussen and Alleyne, 2006; Tun et al., 2023), show that the average gas temperature inside the tank can be predicted with an accuracy of $\pm 5^\circ\text{C}$. This approach is widely used for parametric analyses of refuelling performance (Kuroki et al., 2018; Ortiz Cebolla et al., 2015; Striednig et al., 2014; Tun et al., 2023; Xiao et al., 2018, 2016). This approach reduces computational cost and it can be used to derive refuelling protocols, such as SAE or more advanced (PRHYDE Project, 2020; SAE J2601-1, 2020), as the precision on the evaluation of the final temperature and pressure of the gas tank is sufficient (Ammouri et al., 2023; Charolais et al., 2021). Other researchers opted for analytical models (Xiao et al., 2023). This modelling approach determines the final state of refuelling from input parameters without dynamic simulation, reducing computational cost but lacking dynamic process details. Many studies analyse the overall system, focusing on HRS performance improvement and energy reduction. Some assess high-pressure storage configurations to minimize energy use (Caponi et al., 2022; Farzaneh-Gord et al., 2012; Guo et al., 2016; Reddi et al., 2014; Rothuizen and Rokni, 2014; Serdaroglu et al., 2015; Talpacci et al., 2018). Others examine cooling system energy consumption (Elgowainy et al., 2017b; Talpacci et al., 2018; Wu et al., 2023), monitoring cooling demand without modelling the system. Some studies model entire HRSs to compare technologies like compressed or liquid storage (Schäfer and Klein, 2019), or explore H₂ supply strategies (Elgowainy et al., 2014; Nistor et al., 2016; Reddi et al., 2018, 2014). Some commercial software, like MATLAB Simulink's HRS model (MathWorks, 2023), also simulate complete stations, including compressors, but it lacks on experimental validation. The majority of this studies focus on light-duty vehicle HRS, while HD-FECV requires larger and more expensive HRS's components, thus the interest to better investigate this sector

The purpose of this paper is to present a new HRS modelling tool, called HyFill. The originality of this model lies in its completeness, as it incorporates all the key components of a hydrogen refuelling station (HRS). These include the high-pressure storage system, pressure control valve (PCV), precooling system, heat exchanger (HX), fuelling line, and vehicle storage system. Additionally, the model is distinguished by its focus on heavy-duty mobility, which requires system scaling, and its flexibility to adapt to various station configurations. This study also presents a comparison of the fuelling line and tank model predictions with experimental test results during both refuelling and defueling. Then a demonstration of the tool's potential is presented.

2 METHODOLOGY

HyFill is a multi-physics dynamic tool developed in MATLAB Simulink[®] with a block approach. To each component correspond a different block which is connected to respect the station configuration. This characteristic allows to implement different HRS models with ease. The blocks of the model are described in this chapter.

2.1 Thermodynamic Properties of Hydrogen

HyFill models H₂ thermodynamic behaviour in several components of the HRS, where the operative pressure can range from 20 to 1000 bar and the temperature from -40°C to 150°C . To predict with fair precision the H₂ thermodynamic state, the GERG-2008 equation of state (Kunz and Wagner, 2012) is used to compute pressure, internal energy, enthalpy, and heat capacities from temperature and density. In the case of H₂, this equation is valid for pressure ranging from 0 to 3000 bars and for temperature going from -196°C to 200°C and has a precision of $\pm(0.1 - 0.2)\%$. Thermal conductivity and dynamic viscosity are calculated with the correlation proposed by Molkov et al (2019).

2.2 Tank Model

At the core of the model is the tank model, which is used to predict pressure and temperature in the high-pressure storage system of the station and the vehicle storage system. Thus, the model must be able to describe distinct types of tanks, different nominal working pressures (NWP), and different capacities. Nonetheless it must predict pressure and temperature during both filling and emptying. The tank is a pseudo-1D model, as it is based on the hypothesis of homogeneous gas temperature and pressure in the tank during the refuelling. The heat transfer between the gas and the outside is modelled by the unsteady one-dimensional radial heat conduction equation. To have access to the temperature, mass, and pressure of the gas in the tank, a system of two equations is solved at each time step during the whole filling or emptying simulation; these are the mass balance, the energy balance for a control volume here given by Rothuizen (2013):

$$\begin{cases} \frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{out} \\ \frac{dm u}{dt} = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} - \dot{Q}_{g-w} \end{cases} \quad 1$$

In this equation system, m is the H2 mass in the tank, \dot{m}_{in} and \dot{m}_{out} are the inlet and outlet mass flow rate respectively, u is the specific internal mass energy [Jkg^{-1}], h is the specific mass enthalpy [Jkg^{-1}]. The heat flow from the gas to the tank wall, \dot{Q}_{g-w} [W]:

$$\dot{Q}_{g-w} = S_{in} k_{int} (T - T_{w,r=r_{in}}) \quad 2$$

Where S_{in} is the inner wall surface of the tank [m^2], k_{int} is the inner film heat transfer coefficient [$Wm^{-2}K^{-1}$] determined from the correlation for mixed turbulent and natural convection (Kuroki et al., 2021):

$$Nu = \left((0.17 Re_d^{0.67})^4 + (0.104 Ra^{0.352})^4 \right)^{0.25} \quad 3$$

Where Nu is Nusselt number, Re_d is Reynolds number at the injection, Ra is Rayleigh number. The difference between the filling and emptying model is that in second case the injection velocity is null; thus, Reynolds is null, and Nusselt depends only on the natural convection term, associated with Rayleigh number. $T_{w,r=r_{in}}$ is the temperature of the inner wall of the tank. It is obtained by solving, at a given pressure, the unsteady one-dimensional radial heat conduction equation (assuming azimuthal symmetry as the tank wall temperature is the same along its entire length for a given radius, r), in Equation (4):

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\lambda}{r} \frac{\partial}{\partial r} \left(r \frac{\partial T}{\partial r} \right) \quad 4$$

The boundary conditions necessary to solve this equation being the heat flow from gas to the inner tank wall and the heat flow from the outer tank wall to the ambient (\dot{Q}_{w-a}):

$$\dot{Q}_{w-a} = S_{out} k_{ext} (T_{w,r=r_{out}} - T_a) + \varepsilon_w \sigma S_{out} (T_{w,r=r_{out}}^4 - T_a^4) \quad 5$$

where k_{ext} is the outer film convective heat transfer coefficient kept constant $k_{ext} = 10 [Wm^{-2}K^{-1}]$ (Simonovski et al., 2015), S_{out} is the outer wall surface of the tank, $T_{w,r=r_{out}}$ is the temperature of the outer wall of the tank, T_a is the ambient temperature, ε_w is the emissivity of the external wall of the tank, σ is the Stefan-Boltzmann constant.

2.3 Fuelling line model

The fuelling line model is used to predict the heat transfer during the refuelling of the vehicle, as it can have an important impact on the injection temperature that is a key parameter of the refuelling protocols (Ammouri and Bourgeois, 2018; Kuroki et al., 2018). The thermal model consists in simplifying the pipeline as a single cylindrical smooth pipe with averaged thermal properties and pondered geometric dimensions. The first hypothesis is the conservation of mass, as the incompressible gas has Mach < 0.8. Secondly, the pipe wall temperature is uniform along its radius, as Biot number is 1 (Holman, 2010), and its length, as the longitudinal variation of the wall temperature becomes almost negligible during the refuelling, therefore the longitudinal distribution of temperature can be negligible (Kuroki et al., 2018). The H2 thermophysical properties along the pipeline are also considered as constant, as pressure and temperature difference between inlet and outlet have a negligible impact. The energy balance is:

$$d(mu)/dt = 0 = \dot{m}_{in} (h_{out} - h_{in}) + \dot{Q}_{g-p} \quad 6$$

Thus, to evaluate the heat flux from the gas to the pipe wall \dot{Q}_{p-g} we can use Equation (7) derived from LMTD method (Shah and Sekulić, 2003) and energy conservation:

$$\begin{cases} \frac{dU_{HX}}{dt} = \dot{Q}_{h-HX} + \dot{Q}_{c-HX} + \dot{Q}_{amb-HX} \\ \dot{Q}_{h-HX} = \dot{m}_h c_{p_h} (T_{h_{in}} - T_{h_{out}}) \\ \dot{Q}_{c-HX} = \dot{m}_c c_{p_c} (T_{c_{out}} - T_{c_{in}}) \\ \dot{Q}_{amb-HX} = k_{out} S_{ext_{HX}} (T_{ext} - T_w) \end{cases} \quad 11$$

Where \dot{Q}_{h-HX} , \dot{Q}_{c-HX} , \dot{Q}_{amb-HX} [W] are respectively the heat flux from the hot fluid, cold fluid and ambient to the HX wall for the considered segment. $S_{ext_{HX}}$ [m²] is the external surface of the HX. As demonstrated for the fuelling line (Equation 7) for each side these relationships can be written:

$$\dot{Q}_{h-HX} = (UA)_h (T_{h_{in}} - T_{h_{out}}) / \ln \left(\frac{T_{h_{in}} - T_w}{T_{h_{out}} - T_w} \right) ; \dot{Q}_{c-HX} = (UA)_c (T_{c_{out}} - T_{c_{in}}) / \ln \left(\frac{T_w - T_{c_{out}}}{T_w - T_{c_{in}}} \right) \quad 12$$

Where $(UA)_h$, $(UA)_c$ [WK⁻¹] are respectively the heat transfer coefficient per area of the two sides for the considered segment.

$$UA_h = UA_{h,tot} / n_{HX} ; UA_c = UA_{c,tot} / n_{HX} \quad 13$$

The $UA_{h,tot}$, $UA_{c,tot}$ refers to the entire HX and are calculated from a scale factor (U_{scale}) multiplied by the UA value of the design conditions (UA_{design}). To have a more detailed explanation see Annex 1.

The thermal buffer is a thermal insulated liquid storage tank. In the cooling loop it has the function of increasing the thermal inertia of the system by storing a big amount of HTF at low temperature. The objective is to reduce the overall cooling capacity necessary to cool the H₂ during the cooling peak demand of the refuelling. By neglecting thermal dilatation of the HTF in the buffer tank, mass conservation can be assumed in the tank. Thus, the reservoir can be modelled as an adiabatic volume where the fluid enters at a given temperature and exits at the average temperature of the buffer (T_{buf}). The equation system is:

$$m_{HTF} c_{p,HTF} \frac{dT_{buf}}{dt} = \dot{m}_{in} c_{p,HTF} T_{in} - \dot{m}_{out} c_{p,HTF} T_{buf} \quad 14$$

Where m_{HTF} is the HTF mass contained in the tank, $c_{p,HTF}$ is the heat capacity of the HTF.

There are many configurations of vapor compression cycles that can be used in HRS cooling systems, but the detailed description of its thermo-dynamical behaviour is outside the scope of this work. The first modelling approach aims to determine the power consumption of the system based on the hypothesis that the system is always capable of producing the cooling demand set by the mass flowrate and temperature of the HTF in the buffer, and the outlet temperature which considered constant and equal to the set temperature ($T_{c,in}$). The cooling capacity can be estimated from this equation:

$$\dot{Q}_{cycle} = \dot{m}_{HTF} c_{p,HTF} (T_{buf} - T_{c,in}) \quad 15$$

2.5 Pressure Control Valve

The PCV of the station is model with the flow equation derived from IEC 60534 standard (IEC, 2011), Equation 10. During the simulation, a PID controller simulates the control of the valve by changing the k_V (from 0 to 100%) to respect the pressure ramp defined by the refuelling protocol.

2.6 Cascade High-Pressure Storage System

The cascade high pressure storage system is the storage system of the station that is composed of high pressure tanks of increasing nominal pressure. The refuelling of the vehicle happens thanks to the pressure equilibration between the station and the vehicle storage with a rate guaranteed by the PCV. Starting from the lower pressure level, the cascade storages progressively empty until the pressure equilibrates with the dispenser, then the next pressure level is used. The cascade model thus is a storage model composed of several tanks (section 2.2) divided in different sections with increasing nominal pressure.

3 VALIDATION

The experimental data comes from different test campaigns conducted with similar tests rigs but with different fuelling lines and different tanks in the context of the European PRHYDE Project (PRHYDE Project, 2020) and another experimental campaign. The experimental data allowed to validate the tank and fuelling line model during refuelling and defueling. The characteristics of the tanks and fuelling lines are in **Table 1**. The schematic of the test rigs is shown in **Figure 2**.

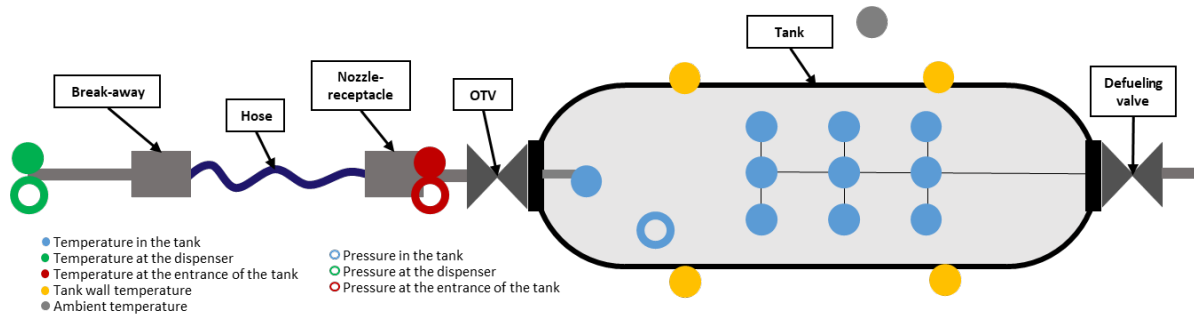


Figure 2 – Experimental test rigs scheme with main components.

The measured data used for the validation of the refuelling are: the mass flow rate flowing from the dispenser to the tank; the dispenser temperature and pressure (T_{disp} , P_{disp}); the injection temperature ($T_{injection}$); the gas pressure in the tank (P_{tank}); the average gas temperature in the tank, which is calculated as the average value of the thermocouples distributed inside the tank to compensate the effect of horizontal and vertical stratification ($T_{g,avg}$). Along with the average temperature maximum ($T_{g,max}$), minimum ($T_{g,min}$), and OTV (T_{OTV}) temperatures are also traced. Instead, for the defueling process only the temperature ($T_{g,avg}$) and the pressure inside the tank (P_{tank}) are used. The H₂ is defueled to the ambient through a venting system with a calibrated orifice. To ensure that the tests results were not depending on tests conditions, the refuelling tests were performed in large variety of refuelling conditions, including pressure ramp rate (PRR varying from 4 to 20 MPa/min, including non constant PRR), initial pressure (from 20 to 150 bar), injection temperature (from -40°C to ambient temperature), ambient temperature (from -30°C to 50°C). The emptying tests are limited by the outflow at 2.5 g/s maximum for safety reasons.

Table 1 - List of geometric and thermal characteristics of the fuelling lines and tanks.

Fuelling line	Unit	Test rig 1	Test rig 2	Test rig 3	Test rig 4
Length	[m]	8.0	8.5	2.4	4.5
Thermal Mass	[kJ/K]	5.7	6.2	4.6	3.3
Kv equivalent	[m ³ /h]	0.095	0.124	0.110	0.124
Tank specifications	Unit	Test rig 1	Test rig 2	Test rig 3	Test rig 4
Type	-	Type IV	Type III	Type IV	Type IV
Tank volume	[l]	244	322	165	300
NWP	[bar]	700	350	700	350
Length/Diameter	-	4.50	9.00	7.33	7.25
Thermal Mass Liner	[kJ/K]	37	40	40	100
Thermal Mass Composite	[kJ/K]	169	107.	122	225
Thermal Mass Boss	[kJ/K]	3	-	5	6

3.1 Comparison with simulations

The overall results of the comparison between the predicted and measured gas average temperature in the tank are resumed in **Table 2**. The comparison is based on the maximum value among the tests for three metrics: the average absolute temperature difference (AA Δ T), which indicates how accurately the temperature was predicted on average; the maximum absolute temperature difference (MA Δ T), which represents the largest deviation between experimental and predicted temperatures; and the end temperature difference (E Δ T), which reflects the final precision of the prediction, and is the most important value. In **Figure 3** there is an example of the comparison of one simulation during a refuelling on Test rig 1. In the chart are the predicted temperature and pressure (in full line) and the experimental values (dotted line). In this test the tank is filled from 35 to 814 bar. The predicted tank average gas temperature is almost super posed with the experimental data. The inlet temperature is over predicted in the first part of the refuelling but then it matches the experimental data. This is due to the assumption of homogeneous wall temperature and the initialisation temperature, which was not measured, but set equal to the ambient temperature. The difference between the measured and predicted pressure is related to the estimation of the $k_{v,eq}$. This method gives satisfactory results for this application, but it also shows some limitations as not all components can be described with a flow coefficient.

Table 2 – Overview of the comparison HyFill against experimental tests. The end temperature prediction precision can be assumed to be $\pm 3^{\circ}\text{C}$.

Variable	Unit	Test rig 1	Test rig 2	Test rig 3	Test rig 4
Tests N°	-	14	18	18	7
AAAT	[$^{\circ}\text{C}$]	2.2	4.5	3	1.5
MAAT	[$^{\circ}\text{C}$]	4.5	8.5	10	5.3
EAT	[$^{\circ}\text{C}$]	± 1.8	± 2.9	± 3.0	± 1.8

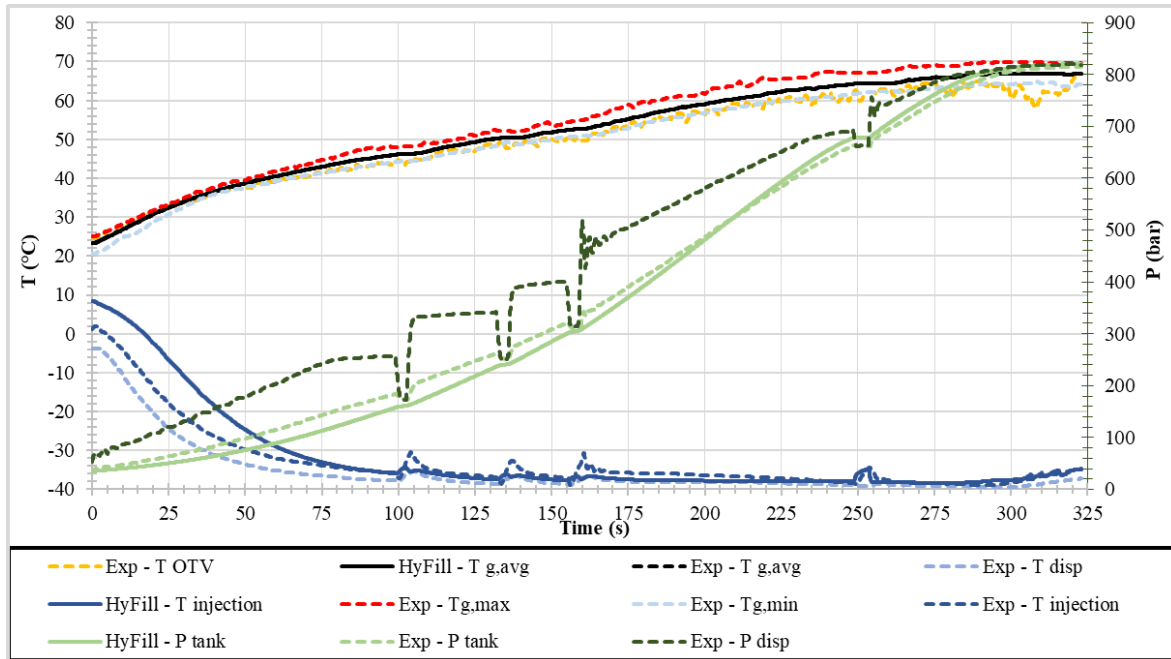


Figure 3 – Test Rig 1 – Comparison between HyFill and experimental results during refuelling.

In **Figure 4** an example of the comparison of one simulation during the defueling of Test rig 4. The experimental data are reported in black, while the simulation results are reported in blue. The gas temperature inside the tank, in continuous line is the average measured value (black) and the calculated value (blue), while in dotted lines there are the maximum and minimum measure values measure by the thermocouple tree. The tank empties from 350 to 50 bar with an average mass flow rate of 1.5 g/s. The ambient temperature is 9°C . In case of tank defueling there is a strong thermal stratification, as it can be seen from the graph, nonetheless the OD approach gives satisfactory results for this application.

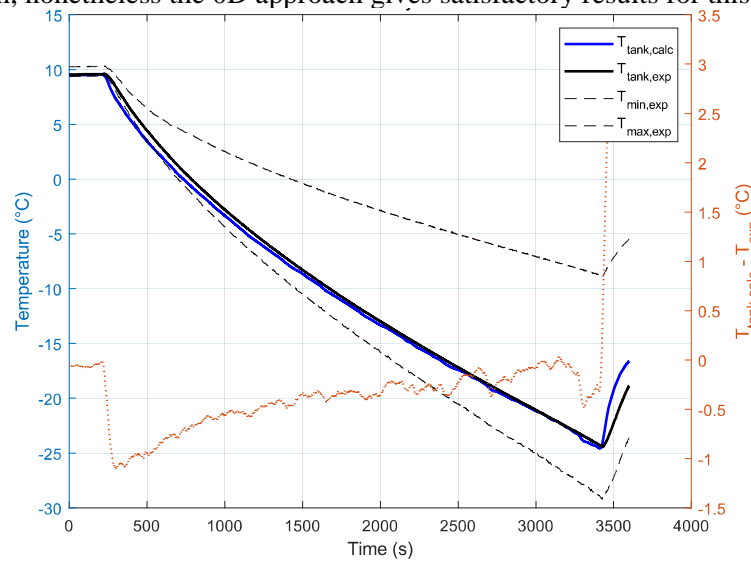


Figure 4 – Test rig 4 - Comparison between HyFill and experimental results during defueling.

4 RESULTS

This section is dedicated to the results of a simulation of the HRS refuelling a HD-FCV. The station design is based on real existing components developed to ensure high speed refuelling (100 kg in 10 min) (RHeadHy Project, 2023) and the configuration is similar to the one described in previous works (Riedl, 2020; Rothuizen and Rokni, 2014), and schematised in **Figure 5**.

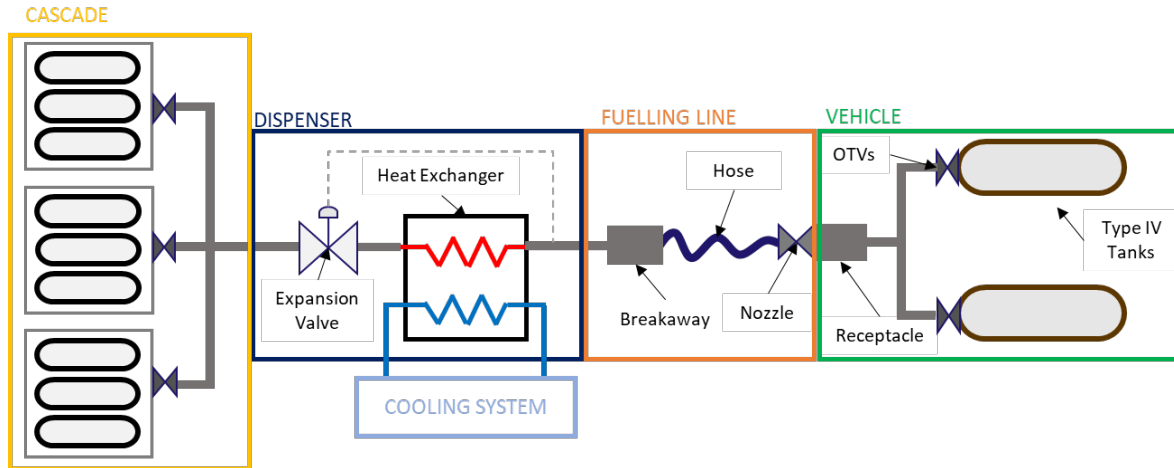


Figure 5 – Station layout.

4.1 HRS characteristics

The station used for this simulation is composed of:

- A pressure level cascade system divided in nine pressure levels (**Table 3**).
- Pressure control valve: maximum flow coefficient 1.33 m³/h.
- Cooling systems:
 - Thermal capacity: 350 kW
 - H₂ outlet temperature: -30°C
 - Heat exchanger UA: 14 kW/K
- Fuelling lines: H70 for heavy-duty refuelling (up to 300 g/s).
- Vehicle storage system: ten tanks with NWP 700 bar and capacity 250 L, which correspond 100 kg.

Table 3 – Capacity and nominal pressure of the cascade storage system pressure levels.

Cascade Level	Unit	1	2	3	4	5	6	7	8	9
Level Volume	[m ³]	15	2.4	2.4	2.5	2.5	1.2	1.2	1.2	1.2
NWP	[bar]	200	500	500	700	700	930	930	930	930
H ₂ mass	[kg]	224	76	76	100	100	56	56	56	56

4.2 HyFill simulation

The evolution of temperature and pressure in the station and vehicle during the refuelling, shown in **Figure 6**, is the main result of the simulation. On the left is the evolution of the temperature inside the vehicle tanks (blue), which maximum respects the safety constraint of 85°C, the temperature at the inlet and outlet of the PCV ($T_{station}$ and $T_{out,PCV}$), where the temperature difference is caused by the Joule-Thomson effect, and the temperature at the outlet of the dispenser (black) and at the injection (light green). The pressure evolution (right graph) shows the subsequential emptying of the cascade system that allows the dispenser to follow the pressure ramp (black) and ensure a safe pressure increase in the vehicle tank (blue). The simulation ends when the cascade system can not dispense more H₂ as the pressure is almost equilibrated. The final state of charge of the vehicle is 95%. The simulation also evaluates the mass flow rate of H₂ from the station to the vehicle, ensuring the respect of the maximum value imposed by the protocol, which is 0.3 g/s, and the thermal power needed to cool down the H₂, which in this case it 230 kW. These type of simulations can be helpful to predict the HRS performance in terms of client satisfaction (final SOC of the vehicle), safety (respect of the refuelling protocol parameters), and energy efficiency, as it determines the energy consumption of the HRS, from the thermal needs of the cooling system and the need of pressurized H₂ to refill the cascade system.

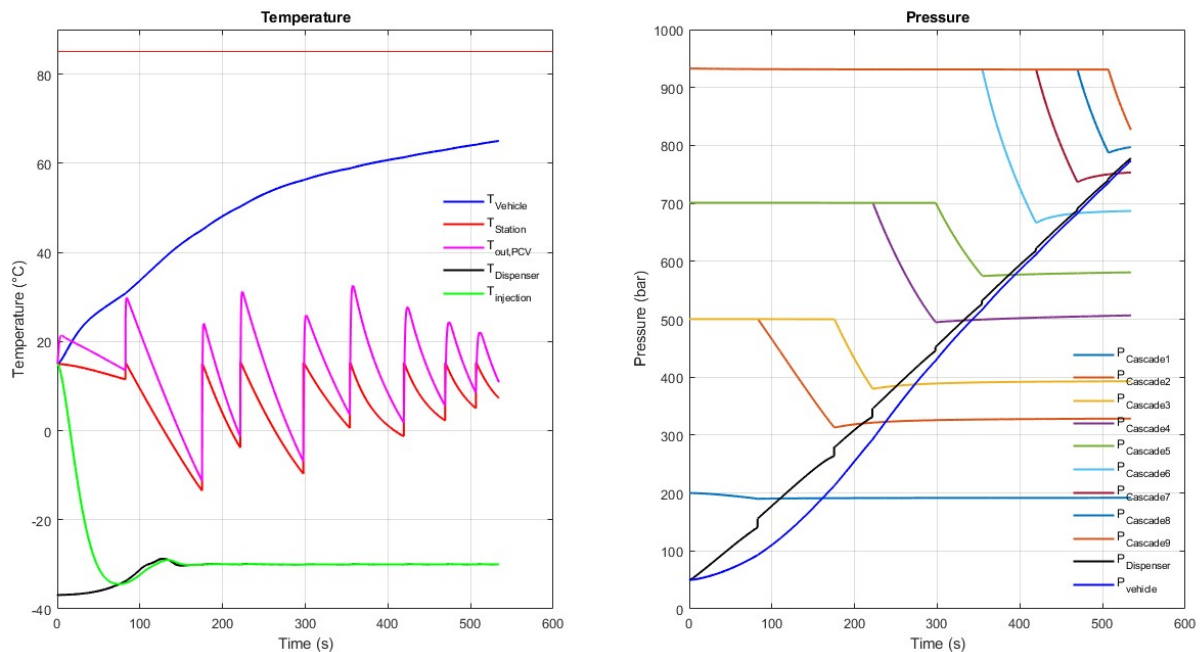


Figure 6 – Evolution of temperature (left) and pressure (right) in different components of the station.

5 CONCLUSIONS

In this paper HyFill, a new HRS simulation tool, has been presented. The methodology used to develop the components model is described. Its main characteristics are its modularity and 0-D modelling approach that allows for flexible and quick simulations of different station designs. The tank and fuelling line model have been validated against experimental tests focused on HD-FCEV refuelling. This allows the model to address question of a wider market than light-duty vehicle. Finally, it has been shown that HyFill can be used to simulate the refuelling of a HD-FCEV and predict the performances of a given station. In perspective, the development of HyFill could enable the simulation of consecutive refuelling of vehicles, the prediction of the station performance on back-to-back refuelling and more complex scenarios. The final objective is to define a new methodology to conceive optimal design for heavy-duty HRS. To obtain these goals the next works will be focused on:

1. Component Validation: a more thorough validation of cooling system.
2. Consecutive Refuelling :integrate the HRS control logic.
3. Station Optimization: Explore optimization strategies for enhancing station performance.

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REFERENCES

- Ammouri, F., Benvenuti, N., Ren, V., Lodier, G., Nouvelot, Q., Guewouo, T., Crouslé, D., Tawk, R., Mathison, S., Kuroki, T., Quong, S., Ruiz, A., Grab, A., Kvasnicka, A., Poulet, B., Kutz, C., Zerta, M., 2023. Engineering models for refueling protocol development: validation and recommendations, in: ICHS 2023. Presented at the International Conference on Hydrogen Safety, Quebec.
- Ammouri, F., Bourgeois, T., 2018. Modeling and validation of heat loss in the filling line of hydrogen station.
- Bourgeois, T., Ammouri, F., Weber, M., Knapik, C., 2015. Evaluating the temperature inside a tank during a filling with highly-pressurized gas. *Int. J. Hydrog. Energy* 40, 11748–11755. <https://doi.org/10.1016/j.ijhydene.2015.01.096>

- Caponi, R., Ferrario, A.M., Bocci, E., Bødker, S., del Zotto, L., 2022. Single-tank storage versus multi-tank cascade system in hydrogen refueling stations for fuel cell buses. *Int. J. Hydrog. Energy* 47, 27633–27645. <https://doi.org/10.1016/j.ijhydene.2022.06.100>
- Charolais, A., Ammouri, F., Vyazmina, E., Nouvelot, Q., Guewouo, T., Greisel, M., Kuroki, T., Mathison, S., 2021. Protocol for Heavy Duty hydrogen refueling: a modeling benchmark, in: *ICHS 2021*. Presented at the International Conference on Hydrogen Safety.
- Cheng, Y., Li, Y., Wang, J., Tam, L., Chen, Y., Wang, Q., Ma, T., 2023. Multi-objective optimization of printed circuit heat exchanger used for hydrogen cooler by exergoeconomic method. *Energy* 262, 125455. <https://doi.org/10.1016/j.energy.2022.125455>
- de Miguel, N., Acosta, B., Baraldi, D., Melideo, R., Ortiz Cebolla, R., Moretto, P., 2016. The role of initial tank temperature on refuelling of on-board hydrogen tanks. *Int. J. Hydrog. Energy* 41, 8606–8615. <https://doi.org/10.1016/j.ijhydene.2016.03.158>
- Ebne-Abbasi, H., Makarov, D., Molkov, V., 2024. CFD model of refuelling through the entire equipment of a hydrogen refuelling station. *Int. J. Hydrog. Energy* 53, 200–207. <https://doi.org/10.1016/j.ijhydene.2023.12.056>
- Elgowainy, A., 2015. Hydrogen Fueling Station Pre-Cooling Analysis.
- Elgowainy, A., Reddi, K., Lee, D.-Y., Rustagi, N., Gupta, E., 2017a. Techno-economic and thermodynamic analysis of pre-cooling systems at gaseous hydrogen refueling stations. *Int. J. Hydrog. Energy* 42, 29067–29079. <https://doi.org/10.1016/j.ijhydene.2017.09.087>
- Elgowainy, A., Reddi, K., Lee, D.-Y., Rustagi, N., Gupta, E., 2017b. Techno-economic and thermodynamic analysis of pre-cooling systems at gaseous hydrogen refueling stations. *Int. J. Hydrog. Energy* 42, 29067–29079. <https://doi.org/10.1016/j.ijhydene.2017.09.087>
- Elgowainy, A., Reddi, K., Sutherland, E., Joseck, F., 2014. Tube-trailer consolidation strategy for reducing hydrogen refueling station costs. *Int. J. Hydrog. Energy* 39, 20197–20206. <https://doi.org/10.1016/j.ijhydene.2014.10.030>
- European Commission, 2024. Reducing CO₂ emissions from heavy-duty vehicles [WWW Document]. URL https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles_en (accessed 12.11.24).
- Farzaneh-Gord, M., Deymi-Dashtebayaz, M., Rahbari, H.R., Niazmand, H., 2012. Effects of storage types and conditions on compressed hydrogen fuelling stations performance. *Int. J. Hydrog. Energy* 37, 3500–3509. <https://doi.org/10.1016/j.ijhydene.2011.11.017>
- Galassi, M.C., Acosta-Iborra, B., Baraldi, D., Bonato, C., Harskamp, F., Frischauf, N., Moretto, P., 2012. Onboard Compressed Hydrogen Storage: Fast Filling Experiments and Simulations. *Energy Procedia* 29, 192–200. <https://doi.org/10.1016/j.egypro.2012.09.024>
- Genovese, M., Cigolotti, V., Jannelli, E., Fragiaco, P., 2023. Hydrogen Refueling Process: Theory, Modeling, and In-Force Applications. *Energies* 16, 2890. <https://doi.org/10.3390/en16062890>
- Guo, J., Xing, L., Hua, Z., Gu, C., Zheng, J., 2016. Optimization of compressed hydrogen gas cycling test system based on multi-stage storage and self-pressurized method. *Int. J. Hydrog. Energy* 41, 16306–16315. <https://doi.org/10.1016/j.ijhydene.2016.05.076>
- Holman, J.P., 2010. Heat transfer, 10. ed. ed, McGraw-Hill series in mechanical engineering. McGraw-Hill Higher Education, Boston, Mass.
- IEC, 2011. Industrial-process control valves Part 2-1: Flow capacity – Sizing equations for fluid flow under installed conditions.
- Incropera, F.P., DeWitt, D.P., Bergman, T.L., Lavine, A.S. (Eds.), 2007. Fundamentals of heat and mass transfer, 6. ed. ed. Wiley, Hoboken, NJ.
- Khan, M.A., Layzell, D., MacKinnon, C., Young, C., 2021. The Techno-Economics of Hydrogen Compression (Technical Brief), Transition Accelerator Technical Briefs. The Transition Accelerator.
- Klopčič, N., Regenfelder, R., Hafner, T., Egger, A., Lechner, F., Winkler, F., Trattner, A., 2024. Investigation of pre-cooling strategies for heavy-duty hydrogen refuelling. *Int. J. Hydrog. Energy* 62, 1030–1042. <https://doi.org/10.1016/j.ijhydene.2024.03.097>
- Kunz, O., Wagner, W., 2012. The GERG-2008 Wide-Range Equation of State for Natural Gases and Other Mixtures: An Expansion of GERG-2004. *J. Chem. Eng. Data* 57, 3032–3091. <https://doi.org/10.1021/je300655b>

- Kuroki, T., Nagasawa, K., Peters, M., Leighton, D., Kurtz, J., Sakoda, N., Monde, M., Takata, Y., 2021. Thermodynamic modeling of hydrogen fueling process from high-pressure storage tank to vehicle tank. *Int. J. Hydrog. Energy* 46, 22004–22017. <https://doi.org/10.1016/j.ijhydene.2021.04.037>
- Kuroki, T., Sakoda, N., Shinzato, K., Monde, M., Takata, Y., 2018. Prediction of transient temperature of hydrogen flowing from pre-cooler of refueling station to inlet of vehicle tank. *Int. J. Hydrog. Energy* 43, 1846–1854. <https://doi.org/10.1016/j.ijhydene.2017.11.033>
- MathWorks, 2023. Hydrogen Refueling Station - MATLAB & Simulink - MathWorks Switzerland [WWW Document]. MathWorks Help Cent. URL <https://ch.mathworks.com/help/hydro/ug/hydrogen-refueling-station.html> (accessed 12.18.23).
- Molkov, V., Dadashzadeh, M., Makarov, D., 2019. Physical model of onboard hydrogen storage tank thermal behaviour during fuelling. *Int. J. Hydrog. Energy* 44, 4374–4384. <https://doi.org/10.1016/j.ijhydene.2018.12.115>
- Nistor, S., Dave, S., Fan, Z., Sooriyabandara, M., 2016. Technical and economic analysis of hydrogen refuelling. *Appl. Energy* 167, 211–220. <https://doi.org/10.1016/j.apenergy.2015.10.094>
- Ortiz Cebolla, R., Acosta, B., de Miguel, N., Moretto, P., 2015. Effect of precooled inlet gas temperature and mass flow rate on final state of charge during hydrogen vehicle refueling. *Int. J. Hydrog. Energy* 40, 4698–4706. <https://doi.org/10.1016/j.ijhydene.2015.02.035>
- Poudel, S., Tun, H., Reddi, K., Elgowainy, A., 2024. Investigation of precooling unit design options in hydrogen refueling station for heavy-duty fuel-cell electric vehicles. *Int. J. Hydrog. Energy* 61, 493–502. <https://doi.org/10.1016/j.ijhydene.2024.02.197>
- PRHYDE Project, 2020. Protocol for heavy duty hydrogen refuelling | PRHYDE Project | Fact Sheet | H2020 [WWW Document]. CORDIS Eur. Comm. URL <https://cordis.europa.eu/project/id/874997> (accessed 8.23.23).
- Ramasamy, V., Richardson, E.S., 2020. Thermal response of high-aspect-ratio hydrogen cylinders undergoing fast-filling. *Int. J. Heat Mass Transf.* 160, 120179. <https://doi.org/10.1016/j.ijheatmasstransfer.2020.120179>
- Rasmussen, B.P., Alleyne, A.G., 2006. *Dynamic Modeling and Advanced Control of Air Conditioning and Refrigeration Systems*.
- Reddi, K., Elgowainy, A., Rustagi, N., Gupta, E., 2018. Two-tier pressure consolidation operation method for hydrogen refueling station cost reduction. *Int. J. Hydrog. Energy* 43, 2919–2929. <https://doi.org/10.1016/j.ijhydene.2017.12.125>
- Reddi, K., Elgowainy, A., Sutherland, E., 2014. Hydrogen refueling station compression and storage optimization with tube-trailer deliveries. *Int. J. Hydrog. Energy* 39, 19169–19181. <https://doi.org/10.1016/j.ijhydene.2014.09.099>
- RHeaDH_y Project, 2023. Refuelling Heavy Duty with very high flow Hydrogen | RHeaDH_y Project | Fact Sheet | HORIZON [WWW Document]. CORDIS Eur. Comm. URL <https://cordis.europa.eu/project/id/101101443> (accessed 8.23.23).
- Riedl, S.M., 2020. Development of a Hydrogen Refueling Station Design Tool. *Int. J. Hydrog. Energy* 45, 1–9. <https://doi.org/10.1016/j.ijhydene.2019.09.234>
- Rothuizen, E., Rokni, M., 2014. Optimization of the overall energy consumption in cascade fueling stations for hydrogen vehicles. *Int. J. Hydrog. Energy* 39, 582–592. <https://doi.org/10.1016/j.ijhydene.2013.10.066>
- Rothuizen, E.D., 2013. *Hydrogen fuelling stations: a thermodynamic analysis of fuelling hydrogen vehicles for personal transportation* : Ph. D. thesis, 1. oplag. ed. DTU Mechanical Engineering : DCAMM, Lyngby.
- SAE J2601-1, 2020. *Fueling Protocol for Gaseous Hydrogen Powered Heavy Duty Vehicles*. SAE International. https://doi.org/10.4271/J2601/2_202307
- Schäfer, S., Klein, H., 2019. Thermodynamical analysis of a hydrogen fueling station via dynamic simulation. *Int. J. Hydrog. Energy* 44, 18240–18254. <https://doi.org/10.1016/j.ijhydene.2019.04.144>
- Serdaroglu, G., Khzouz, M., Gillott, M., Shields, A., Walker, G.S., 2015. The effect of environmental conditions on the operation of a hydrogen refuelling station. *Int. J. Hydrog. Energy* 40, 17153–17162. <https://doi.org/10.1016/j.ijhydene.2015.05.003>

- Shah, R.K., Sekulić, D.P., 2003. Fundamentals of heat exchanger design. Wiley, Hoboken, NJ.
- Simonovski, I., Baraldi, D., Melideo, D., Acosta-Iborra, B., 2015. Thermal simulations of a hydrogen storage tank during fast filling. *Int. J. Hydrog. Energy* 40, 12560–12571. <https://doi.org/10.1016/j.ijhydene.2015.06.114>
- Striednig, M., Brandstätter, S., Sartory, M., Klell, M., 2014. Thermodynamic real gas analysis of a tank filling process. *Int. J. Hydrog. Energy* 39, 8495–8509. <https://doi.org/10.1016/j.ijhydene.2014.03.028>
- Talpacci, E., Reuß, M., Grube, T., Cilibrizzi, P., Gunnella, R., Robinius, M., Stolten, D., 2018. Effect of cascade storage system topology on the cooling energy consumption in fueling stations for hydrogen vehicles. *Int. J. Hydrog. Energy* 43, 6256–6265. <https://doi.org/10.1016/j.ijhydene.2018.02.030>
- Tun, H., Reddi, K., Elgowainy, A., Poudel, S., 2023. Thermodynamic parametric analysis of refueling heavy-duty hydrogen fuel-cell electric vehicles. *Int. J. Hydrog. Energy* 48, 28869–28881. <https://doi.org/10.1016/j.ijhydene.2023.04.075>
- Wu, Y., Geng, X., Chen, J., Shao, S., 2023. Impact of pipelines on cooling demand in the gaseous hydrogen refueling station. *Int. J. Hydrog. Energy* 48, 24412–24425. <https://doi.org/10.1016/j.ijhydene.2023.03.168>
- Xiao, J., Cheng, J., Wang, X., Bénard, P., Chahine, R., 2018. Final hydrogen temperature and mass estimated from refueling parameters. *Int. J. Hydrog. Energy* 43, 22409–22418. <https://doi.org/10.1016/j.ijhydene.2018.10.131>
- Xiao, J., Wang, X., Bénard, P., Chahine, R., 2016. Determining hydrogen pre-cooling temperature from refueling parameters. *Int. J. Hydrog. Energy* 41, 16316–16321. <https://doi.org/10.1016/j.ijhydene.2016.06.084>
- Xiao, J., Xu, N., Cai, W., Zhou, X., Bénard, P., Chahine, R., Tong, L., Yang, T., 2023. Thermodynamic and heat transfer models for refueling hydrogen vehicles: Formulation, validation and application. *Int. J. Hydrog. Energy* S0360319923029385. <https://doi.org/10.1016/j.ijhydene.2023.06.081>

ANNEXE 1 - U Scale Derivation

The scale parameter is used to scale the heat transfer coefficient (h) on the H₂ side with variation of the mass flow rate and H₂ properties in general. The scale parameter is derived from a dimensional analysis of the heat transfer coefficient and the Nusselt number at high Reynolds number, starting from the definition:

$$h = Nu \lambda D_H^{-1} \quad 16$$

As suggested in Klopčič et al. (Klopčič et al., 2024), Gnielinski's correlation (Cheng et al., 2023) for turbulent flow ($4 \cdot 10^3 \leq Re \leq 10^6$, $0.5 \leq Pr \leq 200$) has been used to evaluate Nusselt number. If we consider that for fully developed turbulent flow the friction factor f can be approximated as constant (Incropera et al., 2007), and it depends only on the channel geometry, thus we obtain:

$$Nu(Re, Pr) = \frac{\frac{f}{8} (Re - 1000) Pr}{1 + 12.7 \left(\frac{f}{8}\right)^{0.5} \left(Pr^{\frac{2}{3}} - 1\right)} \propto \frac{f Re Pr}{(f)^{0.5} Pr^{\frac{2}{3}}} \propto Re Pr^{\frac{1}{3}} \propto \frac{\rho u D_H}{\mu} * \left(\frac{c_p \mu}{\lambda}\right)^{\frac{1}{3}} \quad 17$$

Substituting Equation 17 in Equation 16 we can obtain through simplification:

$$h \propto \frac{\rho u D_H}{\mu} \left(\frac{c_p \mu}{\lambda}\right)^{\frac{1}{3}} \frac{\lambda}{D_H} \propto \frac{\rho \frac{\dot{m}}{\rho \pi D_H^2} D_H c_p^{\frac{1}{3}} \lambda^{\frac{2}{3}}}{\mu^{\frac{2}{3}} D_H} \propto \dot{m} c_p^{\frac{1}{3}} \lambda^{\frac{2}{3}} \mu^{-\frac{2}{3}} D_H^{-2} \quad 18$$

Considering that the hydraulic diameter is a geometric characteristic and therefore constant during the operation the scale factor is U_{scale} is:

$$U_{scale} = \dot{m} c_p^{\frac{1}{3}} \lambda^{\frac{2}{3}} \mu^{-\frac{2}{3}} \quad 20$$