A Simulation Toolchain for the Refueling of Hydrogen Vehicles

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Motivation

In order to reduce global warming, the transport sector is progressively decarbonized. Hydrogen propulsion systems are a promising zero-emission variant for heavy-duty vehicles such as buses, trucks and trains. In literature, the refueling process is currently only examined by means of thermodynamic models, where pressure losses are either neglected or treated in a simplified manner [1,2,3]. However, recent investigations reveal the impact of pressure losses within the filling hose, the filling nozzle and the filling receptacle on possible refueling times. Therefore, a simulation tool called **Hydrogen Valve, Piping and Tank Tool (H2VPATT)** was developed for the simulation of the refueling process in early design stages of the vehicle and the respective refueling infrastructure. Pressure losses were incorporated for each component in the H2VPATT model library in order to evaluate accurate refueling times, analyze pressure losses on component level and compute required cold fill temperatures.

Regarding passenger cars, SAE J2601 provides a detailed guideline for the refueling process including average pressure rate ramp (APRR) and final pressure lookup tables to be used in hydrogen dispensers. However, the standard for heavy-duty vehicles, SAE J2601-2, contains only general requirements and boundary conditions without an adopted methodology for the refueling of heavy-duty vehicles. The toolchain described in this abstract is suitable to develop application specific as well as generalized **refueling protocols for heavy-duty vehicles**. The model-based development of a refueling protocol can be subjected to an experimental validation in a further step.

Figure 1. Hydrogen train to be developed in project HyTrain in the Ziller Valley

The simulation toolchain was first applied regarding project **HyTrain** [4]. This project aims at developing and demonstrating the world's first hydrogen narrow-gauge train and its corresponding refueling infrastructure in the Ziller Valley in Austria. The dispensed green hydrogen will be produced on-site by a PEM electrolyzer. HyTrain is funded by the Climate and Energy Fund in Austria within the WIVA P&G Energy Model Region.

Methodology

The development of this easy-to-use modeling approach was inspired by the modeling of electric circuits. Analogous to the role of an electric resistance, a flow resistance R is defined for each component with a pressure loss. The pressure loss for each component can be specified in accordance with the desires of the user in many different ways such as the Kv value of component suppliers, the zeta value, based on an implemented Moody diagram or is automatically taken from data bases for standard geometries (e.g., for t-pieces or pipe bendings). The equations of the resulting network of flow resistances can be derived analogous to the Kirchhoff rules for electrical circuits. The chosen approach results in a system of equations at each node in the model (either at the dispenser, a tank as hydrogen sink or a t-piece) forming an algebraic loop (a circular reference inside the model), which is solved numerically in MATLAB Simulink at each time step. The graphical appearance of MATLAB Simulink and the usage of masks for parametrization enables a model built-up per drag and drop. The various components in the model library are mainly treated as adiabatic and zero-dimensional. The temperature increase due to the Joule-Thomson effect and general fluid-properties of hydrogen are provided by the NIST toolbox REFPROP [5].

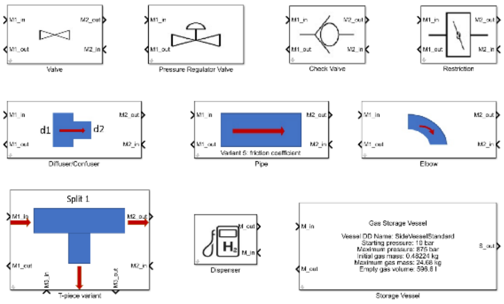

Figure 2. Model library in MATLAB Simulink

The main component in the model library is a detailed model of compressed hydrogen storage systems. The model comprises a 0D thermodynamic model of the gas phase and a 1D discretized heat conduction model through the wall. The heat transfer due to forced and natural convection from hydrogen to the wall is modeled by a Rayleigh and Reynolds number dependent Nusselt correlation [6]:

$$Nu = a\,Re^{b} + c\,Ra^{d}$$

The coefficients and exponents of the correlation were experimentally derived for various tank geometries at the Pascal High Pressure Test Bench at the HyCentA facility.

Results & Discussion

In a first step the model was used to study different piping layouts within the train, available refueling nozzles as well as receptacles, the required number of nozzles and the storage vessel type (type III and type IV). The resulting combinations are compared regarding the theoretically possible refueling time, APRRs and the required cold fill temperature after the hydrogen dispenser in order to comply with SAE J2601-2. Based on organizational constraints a maximum refueling time of 35 minutes can be tolerated. Assuming a type IV vessel the required cold fill temperature can be reduced from - 23 °C to - 1 °C by varying the nozzle type based on currently available nozzle types. From an operational perspective the weight as well as the availability of IrDA communication may be considered, when choosing a nozzle for train application. By using a type III vessel instead of a type IV vessel, the refueling time may be decreased by 17 % at a similar cold fill temperature. In applications with high demands regarding the refueling time a type III vessel may be less sensitive to local temperature variations due to the significantly higher thermal conductivity of the liner.

An analysis of the pressure losses revealed that the main flow restrictions occur in the filling hose and the filling receptacle. The impact of the filling hose diameter and length, the surface roughness of the hose as well as pipes, the piping diameter and the initial tank pressure on the refueling time were additionally studied by means of a sensitivity analysis. The filling hose diameter appears to have the largest impact on the refueling time. Independent of the nozzle type and piping design available filling hoses for H35 refueling come with a nominal diameter of 6.35 mm. A smaller diameter would significantly impair the refueling time, whereas a potential of 4 % refueling time reduction can be stated for an adoption of the filling hose to a larger diameter.

For the elaboration of refueling lookup tables of the train an automated approach was developed based on a series of simulation studies. The resulting lookup tables comprise the APRR, the final pressure (in the tank for refueling with communication or at the dispenser for non-communication refueling) and the possible refueling time depending on the ambient temperature, the initial pressure in the tank before refueling and the dispenser outlet temperature (cold fill temperature). Exemplarily, the APRR lookup tables are illustrated in Figure 3. It can be seen that the possible APRR is almost independent of the initial tank pressure. The dashed line represents combinations resulting in a refueling time lower than 35 minutes (operational constraint). Hence, the tables enable finding the highest possible dispenser temperature fulfilling this refueling time constraint and facilitate a reduction of the required cooling energy in the cold fill aggregate.

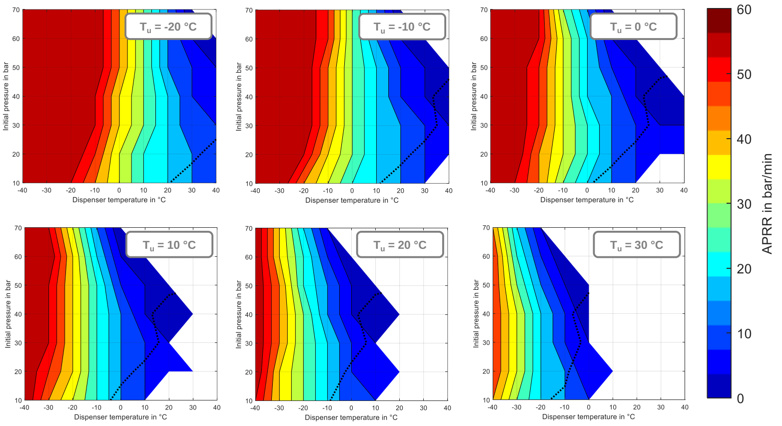

Figure 3. APRR lookup tables depending on the ambient temperature, the initial tank pressure and dispenser outlet temperature

Conclusion & Outlook

The described toolchain called H2VPATT enables a detailed investigation of the refueling process and system layout of hydrogen vehicles (nozzle type, receptacle type, vessel type, etc.). Refueling protocols can be automatically derived based on the described model-based approach. The elaborated refueling protocol for the hydrogen narrow-gauge train developed in project HyTrain will be verified at the Pascal High Pressure Test Bench at the HyCentA facility at a system level in late 2022 and validated in real-life operation in 2025. In a further release of the model library heat transfer to the ambient air of each component and its thermal mass will be included using a lumped parameter network (LPN) model. This facilitates an analysis of the refueling process, when the system is cooled down due to previous cold fills.

References

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