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Overall efficiency comparison between the fueling methods of SAEJ2601 using dynamic simulations

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Abstract

This study concerns MC Formula and the table-based protocol hydrogen fueling methods described in SAE J2601 2016 edition fueling protocols for light duty gaseous hydrogen surface vehicles. It considers the overall efficiency and performance of the two methods. This is achieved by dynamic simulations, using the Dymola hydrogen fueling station library. The MC formula and table-based methods are implemented in the library and different simulations are performed, to evaluate the performance of the two different fueling methods under various conditions. The efficiency is evaluated according to; fueling time, State of Charge levels and total energy consumption. The MC formula is up to 26% faster. The state of charge levels are similar between the table-based and MC formula. The energy consumption for the MC formula is up to 6.9% higher than for the table-based method. Comparing consecutive fuelings without recharging the station, the table-based method is able to fill 7 vehicles and the MC formula 5 vehicles.

Keywords: Hydrogen fueling, SAE J2601, Hydrogen Vehicle, MC formula,
Hydrogen fueling protocols

1. Introduction

Air pollution is a major contributor to climate change and the cause of almost 5.5 million deaths per year [1]. With tailpipe emissions from the transportation sector accounting for 50% to 90% depending on the area [2], many European countries have agreed on banning diesel and gasoline vehicles, some of them starting as soon as 2030 [3]. This has led to a major turn towards clean transportation technologies, both in the private and public sector, with two technologies leading the way: the battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs). Hydrogen is considered by many the energy carrier of the near future, as more and more renewables are penetrating the grid creating the need of large scale energy storage [4]. Hydrogen produced by clean-renewable energy sources is going to be one of the solutions powering the carbon-free transportation sector of the future. The FCEVs market is growing slowly but steadily [5] with California leading the race, having more than half of the total 6500 vehicles deployed globally [6], followed by Japan and Europe. The FCEVs sales are projected to surpass 71500 [7] and while FCEV manufacturing companies such as Toyota are pushing towards increasing the driving range of the new FCEV generation (in 2020) to 700-750 km in a single fueling [8], the demand of hydrogen fueling stations that provide fast an reliable fueling will eventually rise. Currently, two methods of hydrogen fueling are proposed by Society of Automotive Engineers in ”Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles” surface vehicle standard, journal number J2601 (SAE J2601) [9].
These are the "Table-based" method and the "MC formula" method (or "MC formula" for short) [9], both of which are being described in 2.1. The Table-based protocol was the first developed protocol it is fast, reliable, safe and proven. It uses parameters (such as ambient temperature, vehicle’s initial pressure, station pre-cooling capacity etc.) to determine an average pressure ramp rate (APRR) from the lookup tables which will be followed throughout the entire fueling process. The MC formula method on the other hand, takes advantage of active measurements of the fuel’s pre-cooling temperature as well as thermodynamic properties of the vehicle’s storage tank (or compressed hydrogen storage system, CHSS) to actively regulate the fueling speed through a variable pressure ramp rate throughout the fill utilizing a series of formulas and empirical coefficients. This allows for, according to the literature and field tests [10], faster fills than with the table-based method.

1.1. State of the Art

The thermodynamics behind the hydrogen fueling procedure have been studied quite extensively in numerous studies. Comprehensive studies on compressed hydrogen fueling have been made by Dicken and Mérida [11] studying the temperature development inside a compressed hydrogen tank that is being refueled with the use of thermocouples inside the tank. Bourgeois et al. are evaluating a 0D model for real time temperature estimation during the fueling [12]. Further, the effects of variable mass flows and cylinder geometries on the temperature development were studied by Q. Li et al [13], using computational fluid dynamics (CFD) simulations. Lastly, Hosseini et al. have analyzed the process of fueling thermodynamically, using energy and exergy analysis models [14].
Optimization studies of various parameters of the fueling have been performed, varying from optimization on the fueling requirements and how the fueling protocol’s temperature safety boundaries can be pushed further by Bourgeois et al. [15], to station optimization and energy consumption optimization studies by Rothuizen et al. utilizing dynamic simulations [16, 17].

The fueling methods have also been studied, albeit in a lesser amount of publications, with Maus et al. studying the effects of different parameters that led to the protocol development in 2010 [18] and Schneider et al. in 2010 talking about the table-based method implementation, and in 2014, its validation [19, 20]. The MC formula fueling method has not been thoroughly studied since its proposal in 2010 by Harty et al. (funded by Honda) [21], its implementation in the J2601 protocol in 2012 [22] and its field validation study later in 2015 by the same group of people, Mathison et al. [23]. Only one study has, at the time of writing, been released comparing the two fueling methods (the table-based method and the MC formula) in terms of fueling duration and State of Charge levels (SOC) by Krishna et al. in 2017 [10], using the H2SCOPE model.

The thermodynamics of the hydrogen fueling process have been thoroughly studied in numerous articles since 2007 [14, 12, 24, 11, 25]. The table-based method itself and its implementation has also been studied [19] and validated [20]. As for the MC formula, it was proposed by Honda and implemented in the SAE J2601 2014 as a non standard protocol before it in J2601 2016 became a standard protocol along with the table based method. There are a few reported studies about the method itself [21] and its application [22]. Although, both the table-based and MC formula now have been a part of
the SAE 2601 for 6 years, only one study exists that compare and evaluate the two fueling methods [10]. The knowledge about the advantages and disadvantages of the two fueling methods by deeper studies could therefore be improved.

For this study, the MC formula was implemented in the open source hydrogen fueling library for the Dymola software [26]. The model has been verified and validated [27] and it is an extension of the model used in [28]. This study compares the MC formula with the tables-based method from a system’s perspective to evaluate the advantages and disadvantages that exist among the two methods in different fueling scenarios.

Essentially, by modelling the two fueling methods in a hydrogen fueling system model, this study will try to investigate which fueling method is faster under different fueling scenarios, and which fueling method is more energy efficient.

2. Hydrogen Fueling

Gaseous hydrogen fueling is a process that essentially contains the movement of the gas to a target volume (tank). There are two ways of this to happen: Either by direct compression of the gas to a tank using a compressor or by having the gas moved from tank(s) with higher pressure to the target tank which is at lower pressure. Furthermore, hydrogen fueling stations can use both process by utilizing either on-site hydrogen production via electrolyzers, or delivered hydrogen in low pressure storage tanks (most common). Figure 1 shows a simplistic overview of a hydrogen fueling station and system processes variations. From a system perspective, the most effective is fueling by
pressure levelling instead of direct compression due to the higher mass flow rates that can be achieved without being limited by the compressor’s capacity [28]. However, this process - especially when handling hydrogen - is governed by complex thermodynamics that makes its safe handling a top priority. The stored hydrogen in the vehicle’s tank should be at high pressures, typically either 35 or 70 MPa. This is because, as mentioned above, the hydrogen is in gaseous state in order to compensate for the large volume that is needed to store it due to its very low density of only 0.089 kg/m$^3$ (STP). Therefore, commercial FCEVs’ compressed hydrogen storage systems (CHSS) can have 2–10 kg capacity tanks with a volume ranging from 0.0497 m$^3$ to 0.2486 m$^3$, varying depending on pressure class. Furthermore, there are many factors that need to be taken under consideration when filling up a hydrogen tank. When the hydrogen is forced and compressed into a tank, its temperature is rising due to the heat of compression [11]. The temperature inside the tank is, according to the safety instructions in SAE J2601, not allowed to exceed 85°C. For a user friendly fueling experience the hydrogen therefore needs to be pre-cooled to allow for a faster fueling within the safety boundaries. By combining pre-cooling, initial CHHS conditions and ambient conditions it is possible to determine the fastest pressure increase in the CHSS possible without exceeding temperature and pressure limits during the fueling targeting a final pressure corresponding to a SoC of 100%. The need of a user friendly experience of a fast and safe hydrogen fueling has led the SAE into standardizing the fueling procedure according to parameters like the vehicle tank size and capacity, ambient temperature, station’s pre-cooling capacity etc. There are two standardized fueling methods, as described in the Introduction 1, the
2.1. Hydrogen Fueling Methods

The MC formula method and table-based method are available for implementation by hydrogen fueling station manufacturers at their stations. The full implementation of the MC formula method was done into the SAE J2601 2016 standard shortly after the table-based method which was standardised in SAE J2601 2014. All-though, both the MC formula method and table-based protocol are tested by computer simulations and field testing [10, 23, 19, 20] before being accepted into SAE J2601 2016, the scientific studies comparing the two methods are limited. A description of the two methods will be given in this section, focusing on the MC formula, which is the main focus of this study.

2.1.1. Table-based method

The first method described in SAE J2601, is the table-based method. This method describes in detail the process that a hydrogen tank should be refueled at, according to its nominal working pressure (H35 for 35MPa or H70 for 70MPa) and the fuel delivery temperature categories (3 cooling capacity categories symbolized with "T"). The information of the way a vehicle’s tank should be fueled is stored in lookup tables that determine the APRR that should be used as well as the target pressure the tank should reach based on parameters like the ambient temperature, the tank’s initial pressure, the presence of IrDA communications with the tank and if the dispenser is cooled before the fueling or not. An APRR is chosen according to the input data and is held constant until the end of the main fueling. The end of the

7
fueling can be determined either by a target pressure or an SOC level. If communication during fueling is optioned, the fueling stops when the SOC calculated by the vehicle’s measured temperature and pressure is 100%, if no communications apply then it stops according to a target pressure from the table-based method. For both fueling methods, the fueling stops before SoC of 100 % if the maximum operational pressure or maximum vehicle CHSS gas temperature is reached. Close to the end of the fueling, a new APRR might be chosen for the ”Top-Off phase” of the tank although this is a detail applied in real life situations for initial CHSS pressures below 5MPa and it is not going to be examined in this study.

2.1.2. MC formula-based method

The second method described in SAE J2601 is the MC formula. This method was initially developed by Honda and later on, adapted to the conditions and boundaries of the SAE J2601 in which it was also incorporated [10]. It uses an empirically derived equation based on the mass average of the fuel delivery temperature to dynamically calculate the pressure ramp rate (PRR) that determines the fueling speed, and the cold case CHSS thermodynamic properties to dynamically determine the target pressures that should be reached for the fueling to be terminated. It is verified by simulations and also by field testing for its validity [10, 23].

The MC formula’s calculation of the PRR is depended on the temperature measurements of the pre-cooled fuel measured at the dispenser’s outlet, thus built upon the station’s cooling capacity without however dividing the stations in categories according to that cooling capacity. It calculates the PRR for the entire allowable pre-cooling range of -17.5°C to -40°C. The MC for-
mula uses a set of formulae and empirical coefficients (derived by computer simulations) that depend on parameters like the CHSS’s initial pressure, ambient temperature, tank capacity and measured temperature of the incoming fuel to calculate the PRR and the target pressures-limits at any given time.

Fueling part

The MC formula initially uses the temperature measurement of the pre-cooled fuel to calculate the mass average temperature (MAT, Eq 5) and the mass average enthalpy ($h_{\text{ave}}$, Eq 6) at the dispenser. It is having a 30 seconds time window where it does not use this measurement for the calculation of MAT as it uses an expected MAT (set by the station manufacturer according to the station’s cooling capacity) to compensate for the equalization of the temperature of the gas inside the dispenser’s possibly warmer components (piping, hose etc.) and the cooled gas coming from the station. The 30 second delay in the calculation prevents that the MC formula calculation is affected by temperature differences due to cooling of equipment for the first 30 seconds, as a warmer measured hydrogen would results in lower PRR’s and thus a longer fueling time.

The fueling of the MC formula is controlled by the PRR and the target pressure/pressure limit. Utilizing the calculated MAT, an estimation of the total fueling time ($t_{\text{final}}$, Eq 8) is then calculated which is used to derive the PRR needed to complete the fueling in that time. However, because the MAT is dynamically calculated in every second, so is the $t_{\text{final}}$ and subsequently the PRR. If the dispenser’s cooling was not actively measured then the $t_{\text{final}}$ would give a constant PRR similar to the table-based method [10].
2.2. Fueling Thermodynamics

All the models of the components used for the simulations follow the first law of thermodynamics, Newton’s second law, mass conservation and energy balance in the form of momentum and mass balance. The basic theory will be given in this paper, however, a more in-depth analysis of the equations and individually component can be found in Rothuizen et. al. [28] which describe the theory behind the open source Dymola library [26]: "A Thermodynamic Analysis of Fuelling Hydrogen Vehicles for Personal Transportation".

A simplified first law of thermodynamics is shown below in Eq.1 where the gravitational potential energy is neglected due to no height difference between the components and the kinetic energy is included in the enthalpy:

\[
\frac{dE}{dt} = Q - W + \frac{d(m \cdot u)}{dt} + \sum (\dot{m} \cdot h)_m - \sum (\dot{m} \cdot h)_{\text{out}}
\]  

(1)

where \( E \) is the energy, \( Q \) is heat, \( W \) is work, \( m \) is mass, \( u \) is specific internal energy and \( h \) is enthalpy.

For the steady state of the quasi-static models used, the change of energy
equals to zero \( \left( \frac{dE}{dt} = 0 \right) \).

Newton’s second law is used for expressing the change in momentum through the change of pressure as shown in Eq. 2:

\[
\sum F = A_1 \frac{P_1}{dt} - A_2 \frac{P_2}{dt}
\]

where \( F \) is force, \( A \) is area and \( p \) is pressure.

Assuming that \( A_1 = A_2 \) and rewriting \( P = F/A \) then Eq.2 becomes:

\[
dP = P_1 - P_2
\]

The mass balance equation used in the models is derived from the first law of thermodynamics and it is shown in Eq. 4:

\[
\frac{dm}{dt} = \sum \dot{m}_{in} - \sum \dot{m}_{out}
\]

Equation 1 to 4 are present in all models. In components with neglectable volume (i.e the Reduction Valve), the internal energy is not present. However, relevant work and heat contributions are included.

3. MC formula routines

The routines described in SAE J2601 represent a detailed walk-through to develop a station software running the MC fueling method for hydrogen fueling stations. Therefore, there are segments of this description which are essential for security and practical checks on a real station, however, they do not affect a process simulation model that aims at validating the performance.
of the method. As a result, only the essential segments of the MC formula will be explained in detail and the rest will be referenced. An overview of the MC formula routines is shown in Figure 2.

**Figure 2: Process Overview flow chart**

3.1. Mass Average Temperature (MAT) routine

The MAT routine is important for the MC formula as it is the routine that takes the active measurement of the temperature of the incoming fuel. Taking advantage of this temperature measurement at the dispenser, the method can calculate the mass average temperature and enthalpy, which are variables used later for the determination of the pressure ramp rate and target pressure during the fill. There are three different MATs calculated during the fill and one pre-set MAT; $MAT_{expected}$, $MAT_{30}$, $MAT_0$ and $MAT_C$, respectively. Their purpose is described in detail in [9] and the equation that describes them follows below in Eq 5:

$$MAT(i) = \frac{\sum_t(m(t) - m(t-1)) \cdot 0.5 \cdot (T_{fuel(t)} - T_{fuel(t-1)})}{\sum_t(m(t) - m(t-1))}$$ (5)
The mass average enthalpy is calculated in a similar way as seen in Eq 6 and the go-to MAT that is used for the main calculations, the $MAT_C$, is derived by $MAT_{30}$ and $MAT_0$ as seen in Eq 7:

$$h_{ave(t)} = \frac{\sum_i (m(t) - m(t-1)) \cdot 0.5 \cdot (h_{fuel(t)} - h_{fuel(t-1)})}{\sum_i (m(t) - m(t-1))}$$  \hspace{1cm} (6)

$$MAT_C = MAT_{30} \cdot \left( \frac{P_{final} - P_{control}}{P_{final} - P_{trans}} \right) + MAT_0 \cdot \left( \frac{P_{final} - P_{control}}{P_{final} - P_{trans}} \right)$$  \hspace{1cm} (7)

3.2. Final time ($t_{final}$) routine

The second important routine is the $t_{final}$, which is essentially an estimation-calculation of the time needed to fill the CHSS from the minimum pressure ($P_{min}$) to the final pressure ($P_{final}$), without exceeding the general $85^\circ C$ gas temperature limit inside the CHSS at any time [9]. It is a variable calculated in each second of the process’ calculations by utilizing the $MAT_C$ and 4 predetermined coefficients (a,b,c,d) which have been derived by simulations for each case of initial pressures, hot or cold cases and vessel types. The general equation of the $t_{final}$ is:

$$t_{final} = \alpha \cdot \beta \cdot [a \cdot MAT_c^3 + b \cdot MAT_c^2 + c \cdot MAT_c + d]$$  \hspace{1cm} (8)

The $t_{final}$ value is later used for the calculation of the pressure ramp rate.

3.3. Cold Temperature ($T_{cold}$) routine

$T_{cold}$ is the final output of the MC subroutine. It is the cold case final temperature of the gas, which in combination with a target density (essentially $SOC_{target}$) and a target pressure can be calculated. For the calculation of MC – or in the simulations $MC_{cold}$ (because of the cold case assumptions
the \( u_{\text{adiabatic\_cold}} \) must be calculated as well as the \( T_{\text{adiabatic\_cold}} \) for the derivation of the \( c_{\text{v\_cold}} \). Then the \( MC_{\text{cold}} \) is calculated as shown in Eq 9. \( T_{\text{cold}} \) calculations proceed after the MC variable calculation as shown in Eq 10 and it is used to determine the end of fill pressure target.

\[
MC_{\text{cold}} = AC + BC \cdot \ln \left( \frac{U_{\text{adiabatic\_cold}}}{U_{\text{initial\_cold}}} \right) + GC \cdot (1 - \exp(-KC \cdot \Delta t_{\text{cold}}))^{JC} \tag{9}
\]

\[
T_{\text{cold}} = \frac{m_{\text{final\_cold}} \cdot c_{\text{v\_cold}} \cdot T_{\text{adiabatic\_cold}} + MC_{\text{cold}} T_{\text{initial\_cold}}}{MC_{\text{cold}} + m_{\text{final\_cold}} \cdot c_{\text{v\_cold}}} \tag{10}
\]

3.4. Other MC formula routines

There are routines that will not be described as they serve trivial coding purposes for the method itself. The routines are shown in Figure 2 as the initialization routine, the pressure ramp rate routine, the pressure targets and limits routine and the end-of-fill routine. In the initialization routine, various coefficients, parameters and variables are chosen, given starting values and data is imported for the preparation of the calculations that will follow. In the pressure ramp rate routine, the PRR and \( P_{\text{ramp}} \) are calculated utilizing the \( t_{\text{final}} \). In the pressure targets/limits routine, the \( T_{\text{cold}} \) is utilized in combination with a target density (or target SOC) to derive the pressure target that is needed for the termination of the fill along with limitations that may not be exceeded. Finally, the end-of-fill routine serves the purpose of terminating the fueling when the end-of-fill criteria are met or if a limitation has been violated.
4. Results

The fueling simulations was performed in an existing model of a cascade fueling system. Cascade fueling is a commonly used and proven system for commercial fueling stations albeit there are other system configurations that can be applied, they are however outside the scope of this study. For the comparison of the MC formula and the table-based method described in section 2.1, different simulation scenarios were performed. These scenarios were chosen in an effort to cover normal and extreme fueling conditions for a more global assessment of the two methods. The simulations and results are divided into the following scenarios based on ambient temperature:

1. Base Case scenario: $25^\circ C$ ambient temperature, $5MPa$ CHSS initial pressure.
2. Hot Ambient Temperature Scenarios: $45^\circ C$ ambient temperature, $5MPa$ CHSS initial pressure.
3. Cold Ambient Temperature Scenarios: $-30^\circ C$ ambient temperature, $5MPa$ CHSS initial pressure.

Communications fueling is assumed in all three scenarios as all FCEV car manufacturers have infra-red sensors implemented on their cars since 2014. Communication fuelling imply that there is accurate data transfer with infra-red sensors between the vehicle’s CHSS and the station’s nozzle about pressure and temperature development inside the CHSS. Communication can in some cases allow for faster fuelings with both table-based and MC formula [9] as some station does’t measure CHSS volume independently and therefore would utilize a conservative ramp rate pressure ramp without communication. With communication the fastest ramp rate can be obtained without
compromising the safety limitations. In addition, for the sake of simplicity of the model, some technical assumptions are made:

1. All fueling simulations start from a CHSS initial pressure of 5MPa and do not require top-off fueling [9].
2. In the simulations, there are no non-fueling events like leak checks, pause between bank switches etc.
3. There is no "fallback procedure" in the simulation model [9]. The protocol’s process where the pressure ramp rate changes in a certain manner when the cooling capacity changes drastically (complete change in the cooling capacity category, i.e. from T40 fueling to T30) is not simulated as the station is assumed to keep its initial cooling capacity throughout the fueling procedure.

Besides the three simulation scenarios, another two simulation cases were performed for each scenario, varying the CHSS initial pressure (20MPa and 60MPa) which are presented in Appendix A. Lastly, additional simulations were performed changing parameters such communication fueling, cold dispensing, pressure target determination using ending pressure tables instead of MC formula’s formulas etc. A list of all the simulations performed for this project are listed in Appendix A. Additionally, two sets of simulations were performed. The first one to determine the number of fuelings the station can perform from the storage tanks without recovering the pressure after each fueling. This compares the two fueling methods effectiveness fuel vehicles in the event of a compressor break down. The second one is an energy analysis of the two fueling methods comparing the amount of energy needed in order to fuel a vehicle and recovering the pressure in the cascade storage system.
afterwards.

For all the comparisons between the MC formula and the lookup based method the initial conditions are the same and the fueling method will proceed according to SAE J2601, hence the fueling method determines the pressure target and the pressure limit. The final temperature in the CHSS is a consequence of the station design, pressure losses and cooling capacity. The SOC is a density ratio between target density and actual density which is a function of the final pressure in the CHSS and the temperature. The SOC of a lookup based fueling can in principle be both higher or lower than 100% depending on the station and vehicle design. The SOC of the MC is a target and due to the variable PRR it is possible to adjust during the fueling to target an SOC 100%. The comparisons in this paper therefore considers the same station design and initial conditions for both fueling methods and the comparison in done on the performance of the two fueling methods and the final state is a consequence of the fueling method.

4.1. Thermodynamic comparison of the two methods

The assumption for the simulations run to get the results in the following subsection can be find in Appendix A, together with supplementary results for additional case studies of the three scenarios.

4.1.1. Base Case scenario

The simulations in the Base Case were performed in an ambient temperature of 25°C which is a relatively normal fueling temperature considering the protocol’s limits of -40°C to 50°C. Moreover, the cooling capacity of this case is considered to be the best available (cooling capacity of T40 meaning
that the temperature outlet of the heat exchanger is in the range of -40°C
to -33°C). The CHSS is the same size and the table-based method and MC
formula utilize the same input parameters to decide the progression of the
fuelings, hence it is a direct comparison of how the fuelings will progress be-
tween the MC formula and table-based protocol under equal conditions. The
following two figures present collective information graphs in this scenario
for the two methods.

Figure 3: Base Case collective graph for MC formula: 25°C ambient temperature, 5MPa
CHSS initial pressure. Y-axis units depend on the curve examined (see legend)

The results in Figures 3, 4, have a cooling capacity of a standard -38°C
and the fueling is considered to start from a dispenser at ambient temperature
of 25 °C, thus the drop in the temperature of the fuel in the first 30 seconds of
the fueling. As it is seen in both graphs for each method, there is a difference
in fueling time between the two methods. The MC formula achieves a shorter fueling duration than the table-based method by utilizing a variable PRR. From the collective graph in Figure 3 one can observe that the MC formula’s PRR is steady in the first 30 seconds of the fueling. After that, it variates, in contrast with the table-based method’s constant APRR throughout the fill, as seen in the table-based collective graph shown in Figure 4. This variation in the MC formula’s PRR comes in accordance with the different MATs that are being utilized in different stages of the fueling, as explained in Section 2.1.2.

In Figure 5, the path that the $MAT_C$ - which is the MAT that is utilised calculating the PRR - can be seen (red dotted line). $MAT_C$ in the first 30
seconds of the procedure, utilizes the $MAT_{exp}$ (grey dotted line) as it moves along it. After those initial 30 seconds, $MAT_C$ is following the $MAT_{30}$’s path (orange line) that is derived by the active measurement of the pre-cooling temperature. After a transition pressure is reached, it converges to $MAT_0$ (black line), which is calculated since the beginning of the fueling. Therefore, after the active measurements of the cooling temperature take effect, the PRR is increased speeding up the fueling.

Lastly, as the pressure in the CHSS increases (Figure 3), the MC formula drops gradually its PRR until the end of the fueling, reaching the pressure target that was calculated throughout the fill (magenta dotted line). This leads to a pressure development as it is seen in Figure 3 that is fluctuating more than that of the table-based method, having a steeper increase, reaching the pressure target faster.

The constant PRR of $18.5MPa$ (APRR) throughout the fill derived from the protocols tables for the table-based method is causing the fueling to reach the pressure target more than one minute (70 seconds) later than the MC formula. This makes the MC formula 26% faster. The black dotted line indicates the pressure in the storage tanks (measured at the component of Storage Tank 1, 2 and 3 as seen in Figure 3 & 4). The level that this pressure is dropping to shows the utilization of the different pressure storage banks by the MC formula.

The difference in the pressure development between the station pressure and the CHSS pressure is due to the pressure losses between the dispenser and the CHSS. In the case of the MC formula, these losses are larger as shown in Figure 3 as the ”gap” between the station pressure and the CHSS pressure.
is larger than the one for the table-based method (steeper slope of the blue curve in comparison with the smoother magenta curve) as seen in Figure 4. This is expected as the MC formula’s larger PRR in most of the fueling duration results in a significantly larger mass flow rate into the CHSS as it is shown in Figures 3,4. This is translated to larger pressure losses as the mass flow is directly proportional to the velocity and the velocity is directly proportional to pressure losses [28].

As shown in the Table 1 and as mentioned earlier, the MC formula surpasses the table-based method in terms of fueling speed. Furthermore, the MC formula reaches, in this case, a marginally higher SOC level. This happens because in the Base Case simulation, the table-based method terminates due to reaching its pressure target and not its target SOC and the MC formulas pressure target is adapting during the fueling to target an SOC of
100%. This SOC difference in favour of the MC formula translates to a small amount of more mass in the vehicle’s tank which allows for more mileage according to a conservative hydrogen to range calculation [29].

Table 1: Method efficiency data comparison for the Base Case

<table>
<thead>
<tr>
<th></th>
<th>MC formula</th>
<th>Table-based method</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fueling Duration (s)</strong></td>
<td>184.26</td>
<td>248.97</td>
</tr>
<tr>
<td><strong>State of Charge (%)</strong></td>
<td>99.79</td>
<td>98.39</td>
</tr>
<tr>
<td><strong>Mass Dispensed (kg)</strong></td>
<td>5.17</td>
<td>5.10</td>
</tr>
<tr>
<td><strong>Theoretical Mileage (km)</strong></td>
<td>502</td>
<td>495</td>
</tr>
</tbody>
</table>

In the other simulated cases of different CHSS initial pressures, shown in Appendix A, the same trend is followed by most of the results. The MC formula is, in every case performing faster fuelings than the table-based method especially in a non-communication fueling case. The table-based method outweigh the MC formula only in final SOC as the first, whenever it terminates fueling by SOC criteria, it is always higher than the MC formula’s pre-set SOC target of 100% [9]. As a result of the higher SOC level of the table-based method, this is also accompanied with higher mass dispensed and theoretical mileage.

4.1.2. Hot Ambient Temperature Scenarios

The simulations of the Hot Case were performed in an extreme ambient case of 45°C which is only achievable in certain places on the planet and it is 5°C shy of the protocol’s limit in fueling. Furthermore, this case is also worsened by the fact that the cooling capacity is set to T30 (-33 to -26°C)
which slows the fueling as the hydrogen is not cooled as much as in the previous case.

As shown in Table 2, the MC formula fuels almost 4 minutes faster (232.7 seconds or 21.5%) than the table-based method reaching a higher SOC level just shy of the $SOC_{\text{target}}$ of 100% compared to the table-based method of 97.9%, due to the relatively low pressure losses as consequence of a lower mass flow rate. The difference is not large but this stresses out the MC formula’s efficiency of fueling in around the same SOC levels as the table-based method albeit more rapidly. Moreover, due to the higher SOC level of the MC formula, this is also accompanied with slightly higher mass dispensed and theoretical mileage. The other cases of the hot ambient temperature scenario, shown in Appendix A, shows the same relations between the two fueling methods.

<table>
<thead>
<tr>
<th>Table 2: Method efficiency data comparison for the Hot Case</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fueling Duration (s)</strong></td>
</tr>
<tr>
<td>----------------------------</td>
</tr>
<tr>
<td>816.27</td>
</tr>
<tr>
<td><strong>State of Charge (%)</strong></td>
</tr>
<tr>
<td><strong>Mass Dispensed (kg)</strong></td>
</tr>
<tr>
<td><strong>Theoretical Mileage (km)</strong></td>
</tr>
</tbody>
</table>

4.1.3. Cold Ambient Temperature Scenarios

The simulations in this case were also performed in an extreme case of ambient temperature, this time on the other end of the scale at -30$^\circ$C only 10$^\circ$C before the protocols coldest fueling limit. This case has an optimal cooling
capacity of -40°C, as the ambient temperature also promotes it. The combination of low ambient temperature and excellent cooling capacity makes both methods fuel faster than the Base Case, as the components of the station are assumed to be as cold as the ambient temperature, allowing for even higher pressure ramp rates. The combination of low ambient temperature and optimal cooling capacity, result in higher pressure ramp rates for both methods compared to the Base Case with significantly higher mass flows as there is not any concern on exceeding the temperature limits in the CHSS. As shown in Table 3, the MC formula fuels 16.5 seconds (9.4%) faster than the table-based method reaching a higher SOC level of 98.63% compared to the table-based method of 98.23%. This translates also to more mass dispensed and longer theoretical range for the car.

The other cases of this scenario, shown in Appendix A, behave as expected with the MC fueling faster albeit with slightly lower SOC levels. It is important to mention here, that in the case of 60MPa of initial CHSS pressure, no method proceeds to fuel. For the MC formula, as the SOC in that pressure and ambient temperature is 101%, makes the method to calculate a target pressure of 57.8MPa. This is of course lower than the already existing pressure in the tank, resulting in termination of the fueling before it even starts, as the preset $SOC_{target}$ of 100% is reached regardless. Similar case with the table-based method, as its calculated SOC is larger than 100%, which is its target SOC limit for communications fueling termination.
Table 3: Method efficiency data comparison for Cold Case

<table>
<thead>
<tr>
<th>Feature</th>
<th>MC formula</th>
<th>Table-based method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fueling Duration (s)</td>
<td>137.61</td>
<td>151.90</td>
</tr>
<tr>
<td>State of Charge (%)</td>
<td>98.63</td>
<td>98.23</td>
</tr>
<tr>
<td>Mass Dispensed (kg)</td>
<td>5.11</td>
<td>5.09</td>
</tr>
<tr>
<td>Theoretical Mileage (km)</td>
<td>496</td>
<td>494</td>
</tr>
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</table>

5. Energy Analysis of the system using the two different fueling methods

Following the efficiency evaluation of the two fueling methods studying purely the fueling part, the need to study the two methods in terms of energy efficiency by studying the energy consumption arose. The fueling station model was developed further, adding a series of components that brought it closer to real-life station designs. These components included a compressor, an additional heat exchanger (HEX compressor) and a low pressure storage tank (Large Storage Bank). These additions served the purpose of topping up the cascade system’s high pressure storage banks to bring their pressure back to the original levels, preparing them for the fueling of the next FCEV. By studying this more realistic system from an energy perspective, the differences that the two fueling methods have from that aspect can be observed. This analysis has been performed for each fueling scenario in an effort to cover potential energy consumption that different ambient temperatures can cause.

The fueling of the vehicle proceeds exactly as in the 3 scenarios already showed, thus the results for fueling duration, SoC, mass dispensed and theo-
tical milage are the same. The new part is the energy consumption required to do the fuelings and the overall duration which represents the time the station uses to fuel and recover.

Regarding the energy consumption of the system, the only components that require energy (electricity) to operate are the compressor and the cooling system feeding the two heat exchangers. When talking about the energy consumption of a fueling station, if no on-site hydrogen production is utilized, then it is only about those components. The Table 4 below, summarizes the energy consumption of those components after one fueling, for all the different scenarios, using a different fueling method each time (MC formula (MC) and table-based (L.T.)).

Table 4: Energy consumption of the different energy consuming components in each fueling scenario, values given in [kWh]

<table>
<thead>
<tr>
<th>Scenario - Method</th>
<th>Compressor</th>
<th>HEX\textsubscript{compressor}</th>
<th>HEX\textsubscript{fueling}</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case - MC</td>
<td>2.41</td>
<td>0.54</td>
<td>0.82</td>
<td>3.77</td>
</tr>
<tr>
<td>Base case - L.T.</td>
<td>2.20</td>
<td>0.50</td>
<td>0.82</td>
<td>3.52</td>
</tr>
<tr>
<td>Hot Case - MC</td>
<td>2.16</td>
<td>1.25</td>
<td>0.85</td>
<td>4.26</td>
</tr>
<tr>
<td>Hot Case - L.T.</td>
<td>2.23</td>
<td>1.45</td>
<td>0.88</td>
<td>4.56</td>
</tr>
<tr>
<td>Cold Case - MC</td>
<td>1.96</td>
<td>0.15</td>
<td>0.05</td>
<td>2.15</td>
</tr>
<tr>
<td>Cold Case - L.T.</td>
<td>1.92</td>
<td>0.14</td>
<td>0.05</td>
<td>2.11</td>
</tr>
</tbody>
</table>

As it is observed from the previous Table 4, in all the scenarios the most energy consuming component is the compressor which is expected, as it tops up the high pressure tanks pumping hydrogen from the low pressure storage bank. Furthermore, as it is expected, the colder the ambient temperature is,
the lower the energy consumption of the system. This is due to the lower energy demand for cooling the hydrogen in the heat exchangers. Investigating the fueling method for each scenario, utilizing the MC formula seems to be more energy efficient in the Hot Case as the system consumes less energy than by running with the table-based method. This is mainly due to the more compressor work that is required in using the table-based method, as the utilization of the 100 MPa tank is higher than using the MC formula. The mass flow when utilizing the medium pressure tank is higher, thus the pressure loss is higher and less mass can be utilised from the medium tank, the missing mass is instead utilised from the high pressure tank. In the Base and Cold Case though, the opposite happens. This is expected as the higher mass flows that the MC formula uses results to more pressure losses and subsequently the compressor and its heat exchanger must work more to cover the higher pressure lost in the storage tanks. The faster fueling the MC formula provides results in slightly higher energy consumption in mild and cold ambient conditions, as it requires the station to utilize more energy. In the hot ambient conditions on the contrary where the fueling times are significantly higher for both methods and the pressure losses significantly lower, the MC formula consumes less energy than the table-based method.

In Table 5, the difference between the MC formula and the table-based method in terms of overall fueling duration and total energy consumption can be seen. Overall fueling duration takes into account the fueling time plus the time that it is required for the compressor to refill the three high pressure storage tanks from the low pressure storage bank up to their initial conditions (their original pressure that they had before the fueling) to be
Table 5: Overall fueling duration and total energy consumption of the two different methods for each scenario.

<table>
<thead>
<tr>
<th>Scenario - Method</th>
<th>Overall duration [s]</th>
<th>Energy Consumption [kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case - MC</td>
<td>449.87</td>
<td>3.77</td>
</tr>
<tr>
<td>Base case - L.T.</td>
<td>470.35</td>
<td>3.52</td>
</tr>
<tr>
<td>Hot Case - MC</td>
<td>915.87</td>
<td>4.26</td>
</tr>
<tr>
<td>Hot Case - L.T.</td>
<td>1053.11</td>
<td>4.56</td>
</tr>
<tr>
<td>Cold Case - MC</td>
<td>319.92</td>
<td>2.15</td>
</tr>
<tr>
<td>Cold Case - L.T.</td>
<td>407.81</td>
<td>2.11</td>
</tr>
</tbody>
</table>

ready for the next fueling. The process of the filling of the storage tanks from the compressor starts immediately when a storage tank is switched during the fueling. Consequently, the overall duration is affected by the speed of the fueling, as the sooner that there is a storage tank switch, the sooner the compressor will begin to fill that storage tank up. In all the scenarios, the MC formula yields a lower overall fueling duration than the table-based method; from 13.2% less time in the Hot Case up to 24.2% less in the Cold Case.

5.1. Consecutive fuelings

Following the simulations for the study of the energy consumption of the system, a question arose that was proved interesting to answer: In case of a faulty/non-operating compressor, which method can refuel the most cars to a minimum of 50% SOC in this current station capacity setup, utilizing only the cascade system. Consecutive fuelings for both the MC formula and LT method were simulated for the base case without topping up the storage
banks between the fuelings.

![Chart](image)

Figure 6: Consecutive fuelings without compressor operation until SOC is more than 50% for both methods

As it is clear from the graph in Figure 6, the MC formula’s faster but higher pressure loss fueling can provide 5 fuelings before not being able to deliver enough hydrogen in the rate that it is operating with, for a minimum of SOC of 50% in the vehicle. The slower fueling of the table-based method comes on top in this comparison, by being able to fuel 7 cars consecutively, due to less pressure losses. Furthermore, it provides fuelings with higher SOC levels per fueling than the MC formula does. This study assumes that the fuelings continue as if the station was fully operational. It should be noted that in reality the MC formula is much more flexible than the table-based method and if set points at the station are changed when knowledge about a break down is available, it would be able to fuel at slower ramp rates reducing the pressure loss, allowing for higher SoC and more consecutive fuelings.
6. Discussion

This study aimed at the understanding and correct implementation of the MC fueling method to a hydrogen fueling station system model in order to compare the method’s efficiency versus the table-based method of the SAE’s hydrogen fueling protocol. Based on literature review, not many studies are dedicated in studying this method and even fewer exist that compare it with the table-based method. In this project, this gap in literature was tried to be filled from a system perspective. This was achieved by comparing the two methods in respect with fueling times in different ambient temperature scenarios variating different parameters for each scenario such as initial CHSS pressure, communications fueling, cold dispensing etc., but also in respect with energy consumption for each different scenario.

This was made possible by implementing the MC fueling method into an already existing hydrogen fueling system model [26], following the guidelines of the method according to SAE J2601. The implementation led to a model that could switch between the two fueling methods for different simulations. A new component was developed for the model, the ”MC calculations”, which - as its name states - contained all the necessary equations, parameters and variables for the calculations of the method. This model was optimized and a simulation was run based on data from [10]. The results were very similar to the literature, with minor offsets mainly due to the lack of detailed information from said literature. This served as a confirmation of the model which was then ready to simulate this study’s scenarios and cases. Comparing the MC formula with the table-based method for fueling hydro-
gen vehicles, the exact same station outline and parameters has been used for both cases. The only change has been which fueling protocol that has been used. The initial conditions are thus exactly the same, the pressure loss coefficient are the same, the compressor speed and volume is constant and the cooling of the hydrogen was done to the same temperature for both methods. The results are therefore a consequence of the fueling procedures with regards to the choosen station design and vehicle pressure loss.

Regarding the fueling times, the MC formula proved faster in each and every scenario and each scenario’s cases, as it benefits from higher pressure ramp rates that variate according to the measured pre-cooling capacity of the station. This allows for calculated pressure ramp rates that are higher than same-conditions table-based method pressure ramp rates in every case. It should be noted that the results shown and discussed are specific for the station outline chosen and the assumed pressure loss of the vehicle. Some other station design may favor the table-based method with regards to SOC, as the MC formula was made to decrease fueling time the result are representative for this parameter.

In the Base Case, a common real-world case scenario, the difference in fueling time was 26% in favor of the MC formula, which translates to more than a minute less fueling time in a typical 4-minute hydrogen fueling with the table-based method. The MC formula performs even faster fueling in non-communications simulations in this scenario. Furthermore, it reaches the same levels of SOC with the table-based method for each case of the scenario, with only marginal differences in favor of the table-based method
due to the different target SOC mechanics of the latter.

Same trend is followed in a less favourable for hydrogen fueling scenario, the Hot Case. In this case, the high ambient temperatures combined with less than the Base Case’s cooling capacity result in significantly longer fueling times than the Base Case for both methods. The difference between the two methods in terms of fueling time however, are still high with the MC formula fueling 21.5% faster than the table-based method in an overall more than 17 minutes long fueling (using the table-based method). The SoC levels are at the same level for the two methods, with MD formula having a slight advantage in the different cases of initial CHSS pressures higher than the standard 5MPa initial CHSS pressure showcased in the Results.

For a more fast fueling favourable scenario, the Cold ambient temperature scenario, fueling times are significantly less for both methods as they utilize faster pressure ramp rates. Even in the faster fueling times of the Cold ambient scenario, the MC formula proves faster by 23.3%, in an already fast, under 3 minutes, fueling duration. SOC levels in this scenario’s are slightly higher for the table-based method as explained in Cold Case 4.1.3. Both methods results in not fueling the CHSS in the 60MPa initial CHSS pressure case, as the SOC target set is already achieved in this pressure.

In general the comparison between the two methods in regards to the fueling times, the MC formula comes on top, yielding faster fueling times for each scenario’s case, the SOC levels are very similar and which one is higher will depend on the specific station and the vehicle.

Regarding the energy consumption of the system using each fueling method, there are no significant differences between the two methods as the energy
consumption depends mainly on which method is utilizing more hydrogen from the higher pressure storage banks as well as which method has higher pressure losses in the system. The method that yields more pressure losses is mainly the MC formula as the higher pressure ramp rates translates to higher mass flows thus higher pressure losses.

For the Base Case, the MC formula consumes 6.9% more energy than the table-based method due to mainly more compressor work. For the Hot Case, it is the opposite picture, with the table-based method consuming 6.8% more energy, again due to the more compressor work but also this time due to the more cooling work from the heat exchanger after the compressor. This happens for the following reason: The model’s compressor starts refilling the first (40 MPa) high pressure storage tank as soon as the fueling proceeds in a switch to the higher pressure storage tank. As soon as the first tank is refilled, the compressor proceeds with refilling the next one, and so on. In a slow fueling scenario like the Hot Case and especially for the slower filling table-based method, the fueling of i.e the 100 MPa tank at the station, starts before the fueling procedure is over as the previous storage tank (i.e the 700 MPa one) has already been refilled. This leads to higher pressure demand as the fueling is lowering the tanks pressure and the compressor is trying to refill it in the same time, leading to more energy consumption.

One can argue that this is not how a real life compressor in a fueling station works, however, to avoid even more complex coding, this simple solution is applied for in the model and is valid for both methods. The MC formula’s faster fills, make the compressor not having to deal with a tank that is emptying up the same time it is trying to refill it.
In the Cold Case, the MC formula has 1.9% more energy consumption than the table-based method that the lower SOC causes due to the higher utilization of the highest storage tank which translates to less compressor work. For the energy consumption part, it is safe to say that the MC formula provides same if not, for hotter ambient temperatures cases, more energy efficient fuelings with less overall fueling times which further empowers its perks as a fast and energy efficient method.

Following the energy analysis, an interesting study of the number of consecutive fuelings that a station can perform without the use of the compressor (assuming a faulty compressor) to bring back the storage tanks pressure to their initial levels was conducted. The table-based method performed 2 more consecutive fuelings until a satisfactory 50% SOC level was reached than the MC formula, yielding higher SOC levels for each refueling compared to the MC formula. This could indicate that faster is not always better and a station having both methods in its operating software could switch to the table-based method or utilize lower set points in the MC formula in case of a faulty compressor and high demand for fuelings. As the station can utilize more of the stored hydrogen as the pressure ramp rate is lower for the look up tables than for the MC formula, resulting in less pressure losses during the fuellings which again results in the ability to fuel from lower pressures at the station.

7. Conclusion

As an overall conclusion to the comparison of the two methods, the MC formulas was found to be as efficient as the currently used table-based method
in terms of energy efficiency. Rather small differences exist regarding energy consumption in favour of the table-based method (up to 6.9%) when a station is operating at normal (25°C) and colder than normal environments, but the MC formula seems to have the advantage on energy efficiency in warmer environments, with a 6.8% less energy consumption than the table-based method.

The aforementioned same energy efficiency is paired with significantly faster fueling times for the MC formula both in terms of pure fueling duration and also overall fueling time at the station (fueling plus restoring the storage banks to their initial state) that can reach up to 26% faster fuelings for the MC formula (pure fueling time).

Implementing the MC formula in hydrogen fueling stations will yield lower fueling times with similar SOC as the table-based method, thus the MC formula would give better customer satisfaction without compromising the SOC and the energy consumption for a fueling. Its implementation may be a bit more difficult due to its complexity compared to the table-based method but it is worth it according to the findings of this study.

8. Nomenclature

**Roman:**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area, ([m^2])</td>
</tr>
<tr>
<td>a, b, c, d</td>
<td>Coefficients utilized in the (t_{final}) equation, ([-])</td>
</tr>
<tr>
<td>AB, BC, GC, KC, JC</td>
<td>Five constants utilized in the MC Equation, ([-])</td>
</tr>
<tr>
<td>E</td>
<td>Energy, ([J/S])</td>
</tr>
<tr>
<td>F</td>
<td>Force, ([N])</td>
</tr>
</tbody>
</table>
\(c_{v,\text{cold}}\)  Specific heat capacity, \([\frac{J}{kg\cdot K}]\)

\(h\)  Specific enthalpy, \([J/kg]\)

\(m\)  Mass flow rate, \([kg/s]\)

\(m\)  Mass, \([kg]\)

\(MAT\)  Mass Average Temperature, \([K]\)

\(MC\)  Heat capacity, \([J/K]\)

\(P\)  Pressure, \([MPa]\)

\(PRR\)  Pressure ramp rate, \([MPa/min]\)

\(Q\)  Heat, \([J/s]\)

\(RR\)  Ramp rate, \([MPa/min]\)

\(SOC\)  State of charge, [%]

\(T\)  Temperature, \([K]\)

\(t\)  Time, \([s]\)

\(U\)  Internal energy, \([J]\)

\(u\)  Specific internal energy, \([J/kg]\)

\(W\)  Work, \([J/s]\)

\(\alpha\)  Constant for PRR non-linearity, [\(-\)]

\(\beta\)  Constant for pressure tolerance, [\(-\)]

\(\Delta\)  Difference, [\(-\)]

\(\theta\)  Average calculate from start

\(I\)  Initial value

36
2  Final value
30  Average calculated after a total of 30 seconds
adiabatic  Adiabatic
amb  Ambient
ave  Average value
C  Average value
cold  Cold case
control  The target dispenser’s outlet pressure
exp  Calculated expected value
final  Final value
fuel  hydrogen property at nozzle
i  Same term as the \([h_{ave}], [kJ/kg]\)
initial  initial value
max  Maximum value
min  Minimum value
trans  Value midpoint between the initial value and the final value.

Abbreviations:
APRR  Average Pressure Ramp Rate
BEV  Battery Electric Vehicle
CD  Cold Dispenser or Cold Dispensing fueling
CFD  Computational fluid dynamics
CHSS  Compressed Hydrogen Storage System
FCEV  Fuel Cell Electric Vehicle
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IrDA</td>
<td>Infrared Data Association</td>
</tr>
<tr>
<td>MAT</td>
<td>Mass average temperature</td>
</tr>
<tr>
<td>NWP</td>
<td>Nominal Working Pressure</td>
</tr>
<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SOC</td>
<td>State Of Charge</td>
</tr>
<tr>
<td>STP</td>
<td>Standard conditions (temperature and pressure)</td>
</tr>
<tr>
<td>SUV</td>
<td>Sport Utility Vehicle</td>
</tr>
</tbody>
</table>
Appendix A.

The appendix contains the data given to the simulation model and the results for each simulation performed for this paper. The data has been collected in the collective table, table A.7.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Base case</th>
<th>Case CD</th>
<th>Case 1</th>
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<th>Case non</th>
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<tbody>
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<td>25</td>
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<td>APRR for LookupTables (Mpa/min)</td>
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<td>186.35</td>
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<td>M (kg)</td>
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<td>5.32</td>
<td>5.38</td>
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<td>4.81</td>
<td>5.16</td>
<td>5.18</td>
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Figure A.7: Collective table of input variables for the models and the results for each simulation.
References

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URL https://github.com/DTU-TES/Hydrogen-Fuelling-Station
