Development of dispensing hardware for safe fueling of heavy duty vehicles

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ABSTRACT

The development of safe dispensing equipment for the fueling of heavy duty (HD) vehicles is critical to the expansion of this newly and quickly expanding market. This paper discusses the development of a HD dispenser and nozzles assembly (nozzle, hose, breakaway) for these new, larger vehicles where flow rates are more than double compared to light duty (LD) vehicles. This equipment must operate at nominal pressures of 700 bar, -40° C gas temperature, and average flow rate of 5-10 kg/min at a high throughput commercial hydrogen fueling station without leaking hydrogen.

The project surveyed HD vehicle manufacturers, station developers, and component suppliers to determine the basic specifications of the dispensing equipment and nozzle assembly. The team also examined existing codes and standards to determine necessary changes to accommodate HD components. From this information, the team developed a set of specifications which will be used to design the dispensing equipment. In order to meet these goals, the team performed computational fluid dynamic, pressure modelling, and temperature analysis in order to determine the necessary parameters to meet existing safety standards modified for HD fueling. The team also considered user, operational, and maintenance requirements, such as freeze lock which has been an issue which prevents the removal of the nozzle from LD vehicles. The team also performed a failure mode and effects analysis (FMEA) to identify the possible failures in the design. The dispenser and nozzle assembly will be tested separately, and then installed on an innovative, HD fueling station which will use a HD vehicle simulator to test the entire system.

1 Background

1.1 State of the Art

The commercialization and sale of fuel cell electric vehicles (FCEV) has prompted a need for retail sales of hydrogen and dispensing systems that interface with customers in the same manner as petroleum dispensers to establish familiarity and ease of use. Small fleets of fuel cell powered buses are operating around the world and the number of fleets is growing. To compound hydrogen demand, MD and HD FCEVs are being deployed by OEMs for fleet and commercial use (i.e., class 8 semi-trucks, delivery vans, cargo trucks, etc.). Current hydrogen infrastructure relies on LD dispenser designs. The industry is looking to aggressively expand into the HD vehicle markets prompting a need for dispenser systems capable of fueling at faster flow rates and at high pressures to compete with conventional HD vehicles.

Hydrogen dispensers today are capable of refueling LD vehicles per Society of Automotive Engineers (SAE) J2601 at a typical throughput of less than 200 kg/day. Limitations of dispensers include integrated system controls, cost, reliability, and high flow rate capability. The average hydrogen dispensed for fuel cell powered passenger vehicles is approximately 4-6 kg. Current fuel cell transit buses are capable of storing up to 50 kg of hydrogen or more at 35 MPa pressures. Preliminary designs for class 8 semi-trucks may utilize even more on-board hydrogen storage to achieve mileage expectations at 70 MPa dispensers. In addition to flow rates, appropriate hydrogen thermal management is key to achieving accurate fills without further compromising station size.

Currently, high flow hydrogen nozzles assemblies available for HD vehicles are limited to 35 MPa nominal pressure and do not meet the higher pressure and the higher flow requirement of HD vehicles. In addition, nozzles assemblies are one of the biggest sources of maintenance costs and downtime for LD stations. The foremost issue is nozzle freeze which prevents the nozzle from being removed from the receptacle for up to 20 minutes. In order to address this, the system will contain an innovative dry air purging system which is being used on LD stations today.

In order to accelerate the introduction of hydrogen HD vehicle and infrastructure, the U. S. Department of Energy awarded (Cooperative Agreement DE-EE0008817) the team of Electricore (prime), Bennett Pumps, Co. (dispenser supplier), WEH Technologies, Inc. USA & GmbH (component supplier), National Renewable Energy Laboratory (NREL demonstration site) and Quong & Associates, Inc. (technical support) a project to design and manufacture a high pressure, high flow nozzle assembly for HD vehicles. The demonstration of components will be done at NREL's Hydrogen Infrastructure Testing and Research Facility (HITRF).

1.2 Specifications and standards

The project team did extensive research into the specifications and standards related to dispensers and nozzle assemblies. They contacted 22 companies and organizations, including two truck manufacturers, and eight hydrogen station providers. Based upon their research, the team developed a detailed list of specifications and standards which they will use as a guideline to design their equipment. Table 1 shows the high-level specifications which will allow the hydrogen HD vehicle to have equivalent fueling times and range as diesel and other liquid fueled vehicles. The component level specifications are listed in Annex A.

Table 1: Overall specifications

Overall	**Units**	**Min**	**Max**	**Requirement**
Maximum H2 dispensed per fueling	kg		100	
Target fueling time for maximum H2 dispensed	min		10	
Time between fueling	min		3	
Maximum allowable working pressure	MPa		96.6	
Average flow rate	g/s		180	
Peak flow rate	g/s		300	
Ambient temperature	ºC	-40	65	
Relative humidity	%	0	100	
Outdoor operations				Operates under rain, snow, wind, sun
Materials compatibility				All materials exposed to hydrogen shall be compatible and not introduce impurities at the designed pressures and temperatures

2 Dispenser

2.1 Design

The HD hydrogen dispenser design is derived from the LD dispensers Bennett Pump currently manufactures. Figure 1 displays a basic piping and instrumentation diagram (P&ID) for the HD application, making sure that redundant safety checks and components were in place for safe operation of the HD dispenser.

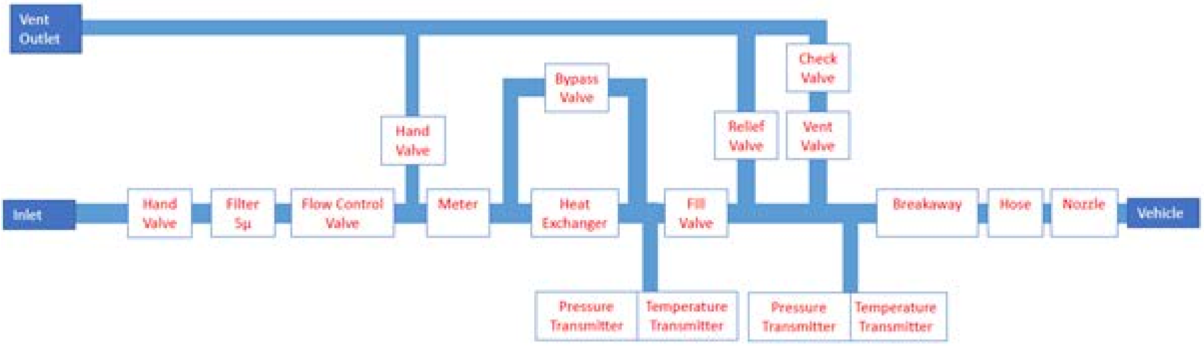


Figure 1: Piping and instrumentation diagram of Bennett heavy duty dispenser

Once the critical fueling components were determined, multiple suppliers of the hydrogen components were contacted and provided operational gas temperature, gas pressure, ambient temperature and the maximum flow rate desired. From this information larger sized components were selected, but not without some challenges, including physical size of components, availability and being able to meet the desired flowrate.

A mass flow meter is required for the fueling protocol and to measure the amount of hydrogen dispensed and sold to the customer. Currently, there is only one supplier that makes these meters for LD dispensers which can withstand the high pressure and cold temperatures associated with hydrogen fueling. The team contacted three suppliers, and the supplier which provides flow meters for LD applications was the only one who had an acceptable solution for the metering. This meter was still in developmental testing at the time of inquiry, but is now released and ready for production.

The next critical step is the component placement in the dispenser, which can be seen in Figure 2 below. All of the components used in the HD hydrogen dispenser are significantly larger in physical size than in the LD hydrogen dispenser. One of the design constraints is to keep a footprint of a standard fueling dispenser, so component size is a critical design factor.

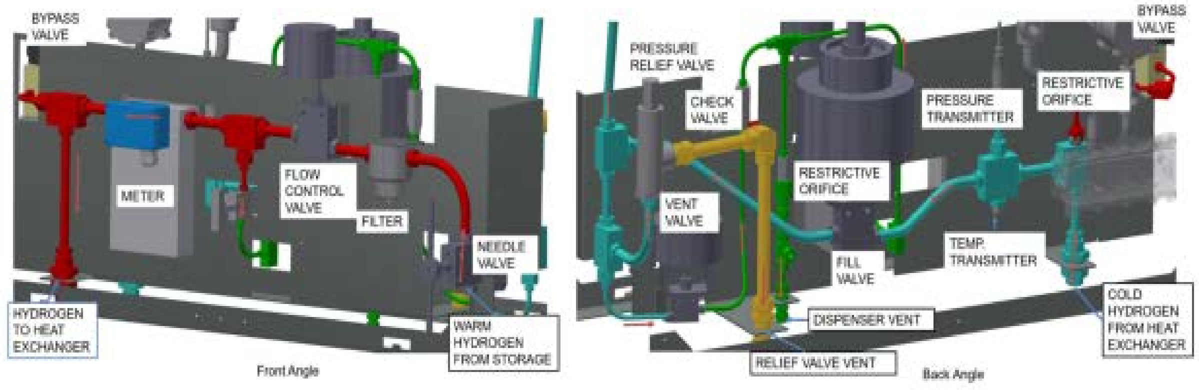


Figure 2: Component layout

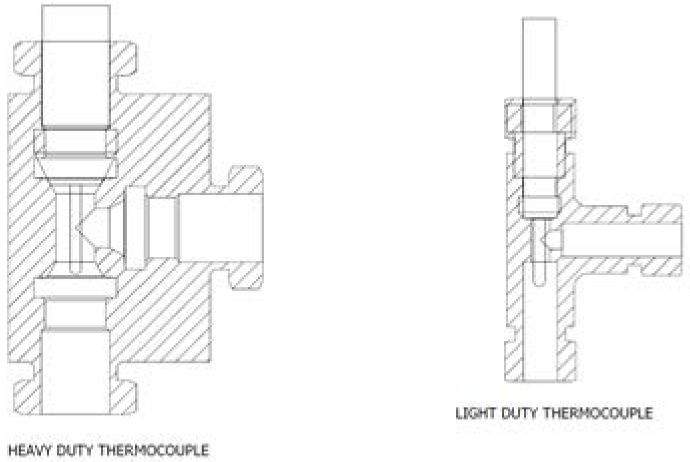
A decision matrix was used to aid in the determination for the fill and bypass valves, which is shown in Table 2. Factors to consider included cost, lead time, physical size, flowrate, and reliability. The cost and lead time are more favorable for the air actuated valve, as the electric solenoid valve does not currently exist and required funding for development. The main benefit of the electric solenoid valve is the small size of the valve. Flow rate and reliability (when comparing a smaller and known electric solenoid valve) show similar results for the evaluation. The team chose to move forward with the air actuated valves.

Table 2: Decision matrix for valves

Decision Factors	Air Actuated Valve	Electric Solenoid Valve
Cost	x	🟥
Lead time	x	🟥
Size	🟥	x
Flow Rate	x	x
Reliability	x	x
Total	**4**	**3**

Special consideration must be taken with the placement of each component to reduce the number of bends to keep the high flow rate required in the HD application. There is also consideration for ease of service and maintenance once the dispenser is in operation. It is important for the components to be accessible for preventive maintenance schedules to ensure safety and longevity of the dispenser.

Detail in the component layout is very important. For instance, the installation of the thermocouple and the accuracy of the temperature readings is critical to the safe operation of the HD hydrogen dispenser. As shown in Figure 3 below, a larger fitting was selected to improve the gas flow around the thermocouple probe; also making sure it is deep enough in the housing for accurate readings, which could pose a safety threat if inaccurate.



HEAVY DUTY THERMOCOUPLE

LIGHT DUTY THERMOCOUPLE

Figure 3: Heavy duty and light duty thermocouple Installation

With the critical fueling component selection, the team documented maximum pressure, temperature ranges and Cv values on all of the components being reviewed. These values were used as input data for the computational fluid dynamic (CFD) software. The pressure drop is proportionally related to the flow rate and inversely proportional to the Cv, and minimizing it is critical in order to reduce the supply pressure that is required to achieve the fueling times targets.

2.2 Preliminary CFD Modeling

The data obtained from the suppliers was entered into the CFD software provided by Seitz Valves and flow calculations were conducted, while monitoring the pressure drop and temperature to make sure the correct size components are selected to achieve the desired flow rate. Multiple iterations of the CFD analysis were ran and used in the selection of the critical fueling components. The CFD analysis will be validated with a controlled laboratory test using a few select components in the fueling system.

The first CFD modelling matched the current LD flow rates to confirm the output of the software and component data. This was used as a baseline as each iteration of the CFD modelling increased the orifice size. This allowed us to confirm the flowrate of the HD application. Initial inner diameter (ID) of 5.2 mm was used along with 4.5 m of straight tubing that is inside the dispenser, and double 90° angles to simulate the three valves in the dispenser: shutoff valve, control valve, and fill valve. The outlet pressure was fixed at 10 MPa, gas temperature at -15 ºC, and flowrate of 15 kg/min. The overall pressure drop of the dispenser at the various tubing ID is shown in Table 3, stopping at 11.1 mm due to satisfactory pressure drop results.

Table 3: Overview of pressure drop for dispenser

Inner diameter d [mm]	Δp [MPa]
5.2	44.5
7.9	15.3
11.1	7.0

The pressure regulating valve selection was based upon the CFD modelling. Information from the supplier on the valve options had Cv values of 0.3 and 1.3. Through the use of the CFD modelling, the data showed that the Cv value was too low for the HD application. Decision to change this valve to a flow control valve was made since it has a Cv value of 2.5 and showed successful results in the CFD modeling. Additionally, three filter manufacturers were contacted with the desired design requirements and all three came back with acceptable solutions. The Cv value among cost, lead times and physical size were compared for use in the dispenser. The team decided to pursue the filter with the largest Cv value to help achieve the maximum flow rate. Other non-critical fueling components were selected after the CFD flow calculations were completed for use in the HD dispenser hydraulics. The breakdown of the individual components based upon on the 11.1 mm ID flow calculation is shown in Table 4.

Table 4: Pressure drop of critical fueling components:

Component	Δp [MPa]
Needle Valve	1.8
Filter	0.4
Flow Control Valve	1.8
Meter	0.6
Heat Exchanger	0.2
Fill Valve	1.0
Linear Losses	1.2

3 Nozzle Assembly

The fundamental question for the design of the nozzle assembly for the HD application is what flow area is required to achieve sufficient mass flow at an acceptable pressure drop? The pressure loss decreases with a larger free-flowing area. However, this increases the necessary wall thickness of the pressure-bearing components and thus the cost and weight of the components which makes handling more difficult. Concerning the filling hose, the stiffness is increased in addition to the weight. For this reason, an abstract CFD calculation was performed in order to determine the necessary minimum flow area to which the components are to be designed.

3.1 Preliminary CFD Calculation

In order to make an estimate for the necessary ID, a simple CFD model was built. This CFD model consists of a round double 90° elbow and a 4 meter long pipe as shown in Figure 4.

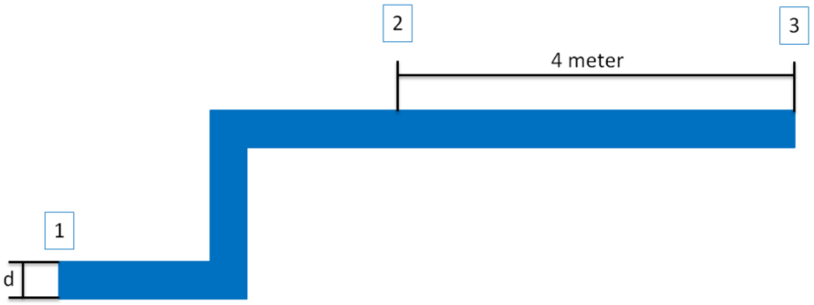


Figure 4: CFD Model of nozzle assembly

The double 90° elbow simulates the valves which will be included in the breakaway device and the nozzle whereas the 4 meter pipe simulates the hose.

Specifications given in Chapter 7 of SAE J2601_202005 [1] were used as boundary conditions and scaled to the high flow application.

Table 5: Overview of boundary conditions

Pressure Point 3	10 MPa
Gas Temperature	-15 °C
Mass flow	250 g/s

The mass flow was calculated according to the specifications, where a maximum pressure drop of 15 MPa from the breakaway device to the nozzle's exit is defined at a mass flow 1.5 times the average mass flow. For the 70 MPa high flow application an average mass flow of 10 kg/min is given, and so the 1.5 times is 15 kg/min or 250 g/s.

The diameter, d, was adapted in order to find the optimum. The selection of the dimensions for the diameter was made on the basis of the ID of available high-pressure pipes. The Soave-Redlich-Kwong real gas approach was used as the material model.

Table 6: Overview of CFD-calculation

Inner diameter d [mm]	$\Delta p_{1->2}$ [MPa]	$\Delta p_{2->3}$ [MPa]
5.2	4.9	28.6
7.9	2.8	5.7
11.1	1.0	1.2

Four deflections are expected for the refueling system from breakaway to the end of the nozzle. This results in the following expected pressure losses for the system:

Table 7: Overview of pressure drop

Inner diameter d [mm]	Δp [MPa]
5.2	48.2
7.9	16.9
11.1	5.2

According to ISO 19880-1:2020 [2], 15 MPa is considered as an acceptable pressure drop. Based on Table 7, the components of the refueling system are therefore designed provisionally with an ID of 12 mm to include a margin of error.

3.2 Refueling system concepts

The team evaluated two (2) different nozzle designs. The first design (Figure 5 below) corresponds to an upscaling of WEH's current design for the CNG TK22 nozzle – considering a much larger flow area and the required pressure resistance of materials used for the H70 HD filling service.

The second design (Figure 6 below) corresponds to a new, much simpler design using fewer parts on the mechanical side and substituting some of them with mechatronic devices that will communicate to the station to satisfy filling and safety requirements given by the international standards. The main functionality of this new design is comparable to WEH's CNG TK24. This approach includes a solenoid driven 3/2 shut-off valve which will be a permanent part of the front of the nozzle being connectable to a venting line. This reduces the volume that must be vented after each fueling, especially when using large diameters. Thus, this concept improves the economy of the fueling station.

According to ISO 17268:2020 and other international standards, there are three different types of nozzles depending on their functionality in terms of shutting and venting the gas. Whereas the first approach can be considered as type C, the second one can be defined as type B – or even type C – depending on the design of the 3/2 valve. Since a type C nozzle must be vented before it can be removed from the vehicle, it is easier to handle, but the hydrogen is lost to the atmosphere. This gives the type B nozzle with venting line some advantages to the station owner.

If the supply line between the station shutoff valve and the nozzle has a length of 6 m and an inner diameter (ID) of 12 mm, 36 g of hydrogen is saved per fueling operation at a final pressure of 87.5 MPa and temperature of –40°C. Or, in other words, 4 kg will be saved per 100 fuelings. In addition, this volume does not need to be compressed for the next fueling. An additional low pressure venting line is required to vent the minimal amount of hydrogen in the nozzle. To protect the venting line from high pressure, which could theoretically be applied in the event of a failure of the check valve in the receptacle, a throttle is installed in the outlet of the 3/2-way shut-off valve.

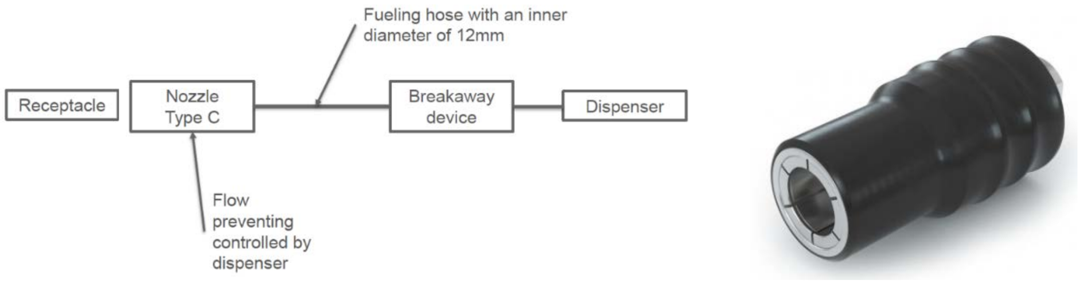


Figure 5: Type C nozzle with one hose and one breakaway device and WEH TK22 CNG nozzle

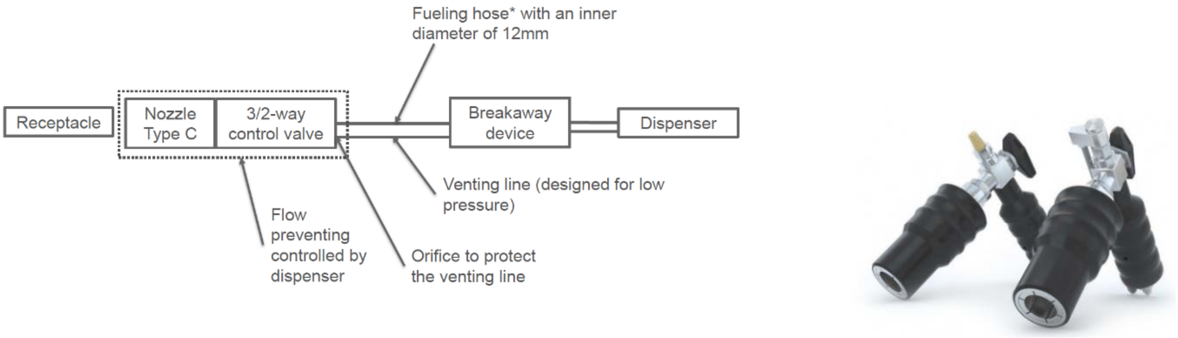


Figure 6: Type B nozzle with venting line and one breakaway device and WEH TK24 CNG nozzle

Although both approaches will offer a push on/off action like existing hydrogen nozzles, scaling an existing design creates two different difficulties related to a) the actual flow we can make through the 12 mm planned ID of the nozzle and b) the related forces on the manual operation of the sleeve.

The team also compared a large diameter filling or several hoses that together form the same flowable area. Experience in the H35 range with several parallel hoses shows that these are easier to handle than a single much larger and more rigid one. However, care must be taken to ensure that the force of the hoses is applied to the breakaway device so that it releases properly in the desired range.

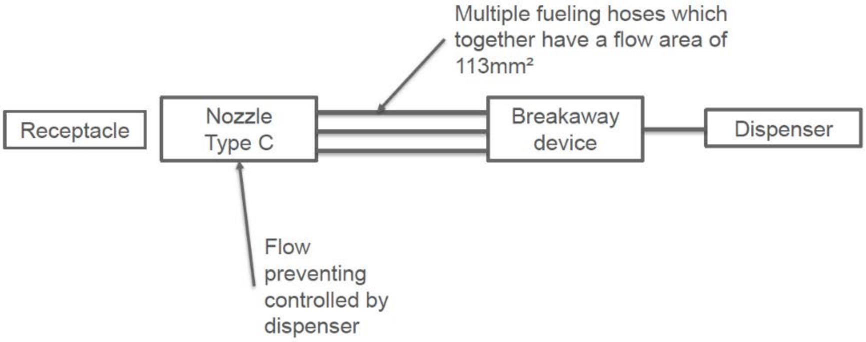


Figure 7: Concept #2 Type C nozzle with multiple hoses and one breakaway device

The team considered not only multiple hoses, but also multiple breakaway devices. Each individual hose is attached to its own breakaway device. This has the advantage that breakaway devices for the H70 high flow application have and are already available and used in the field. However, this further worsens the problem already mentioned in Concept #2 above with the uniform introduction of forces into the breakaway devices.

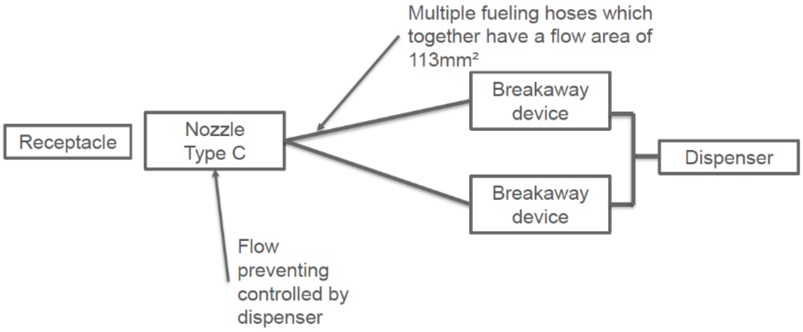


Figure 8:Type C nozzle with multiple hoses and multiple breakaway devices

The team discussed the nozzle assembly options with several key industry stakeholders. The results of the survey indicate that industry prefers the Type C nozzle with a single hose and breakaway due to the simplicity. The loss of hydrogen was less of a concern due to the small amount.

4 Next Steps

4.1 Advanced CFD Modeling

The team conducted preliminary flow modelling to ensure that the dispenser and nozzle are properly sized to avoid pressure drop issues during fueling (components are oversized). Therefore, the team conducted more detailed flow modeling using NREL's H2Fills model. The model considers components starting with the hydrogen station storage tanks all the way through the dispenser, nozzle, and into a vehicle's storage tanks. The model functions by inputting the dimensions and Cv values for the various components (piping, valves, breakaway, hose, nozzle, vehicle tanks, etc.) and calculates the temperature, pressure, and mass flow rate of hydrogen passing through each component (see figure below).

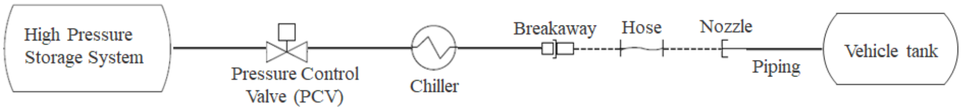


Figure 9: Schematic of components for modeling

The H2Fills model operates under assumptions contained in the SAE J2601 fueling protocols standards. There are two primary operating limits that cannot be violated during fueling, an upper temperature limit of 85°C (based on hydrogen tank plastic liner integrity) and upper pressure limit (dictated by the structural strength of the Type IV composite pressure vessel). The H2Fills model maintains the boundary conditions to keep temperatures and pressures within the specification. Several input parameters are chosen to run the simulations, considering the following:

- Mass Target = 70 kg
- Ambient Temperature = 18°C
- Average Pressure Ramp Rate (APRR) = 10 MPa (appropriate for DOE HD target)
- Initial Tank Pressures = 2 MPa
- Hydrogen Precooling = -40°C (standard precooling temperature)
- Target State of Charge (SOC) = 99%

The preliminary results show an 8-minute fill with a peak fueling rate of 11.96 kg/min and an average fueling rate of 8.19 kg/min. The average fueling rate metric for the project is 10 kg/min. The figure below shows the mass flow profile of the proposed design. NREL’s HD station is capable of 20 kg/min flow rates, which should accommodate projected rates shown.

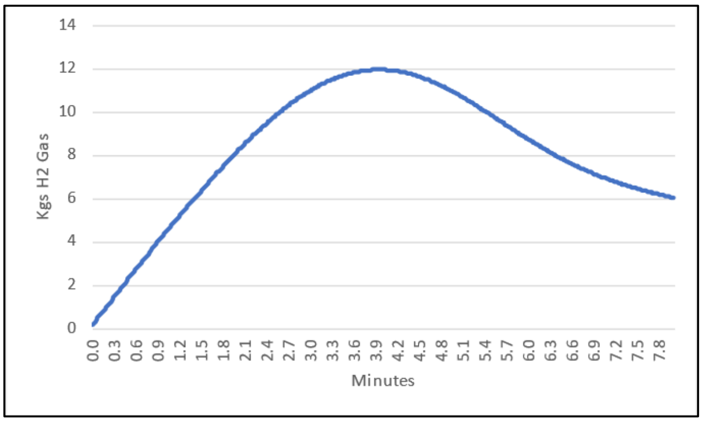


Figure 10: Mass flow profile of the proposed design

The model indicates that there is a potential average pressure drop across the dispenser/nozzle system of 11.31 MPa and a maximum observed pressure drop of 17.69 MPa. Target pressure drop from the breakaway to the vehicle tank is 35 MPa according to SAE J2601. Results from H2Fills show the potential average pressure drop from the breakaway device to the vehicle’s hydrogen storage tanks is 7.27 MPa with a maximum observed pressure drop of 12.92 MPa. which is below the target. The figures below show the dispenser and nozzle system pressure drop as well as the breakaway to hydrogen storage tank pressure drop.

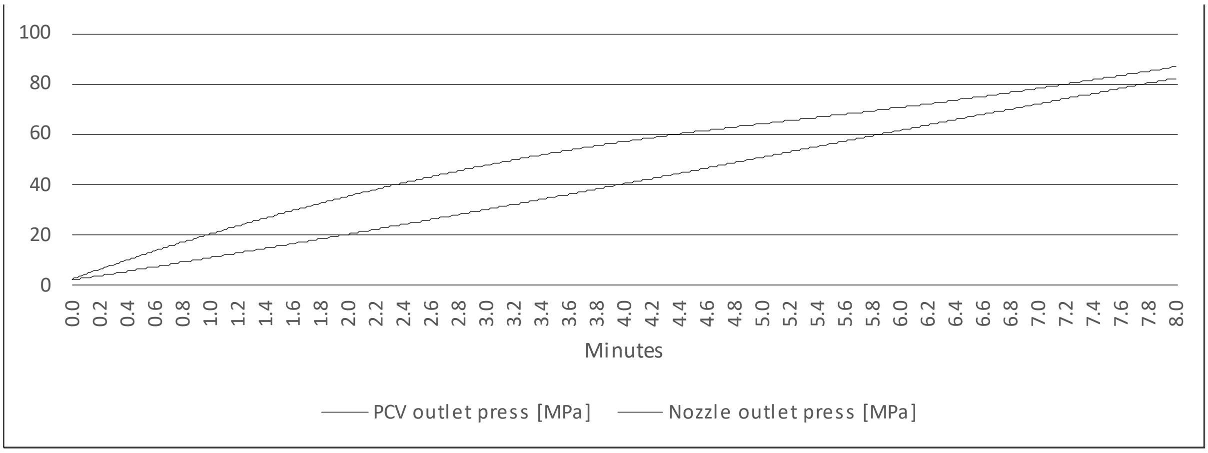


Figure 11: Dispenser/Nozzle System Pressure Drop (MPa)

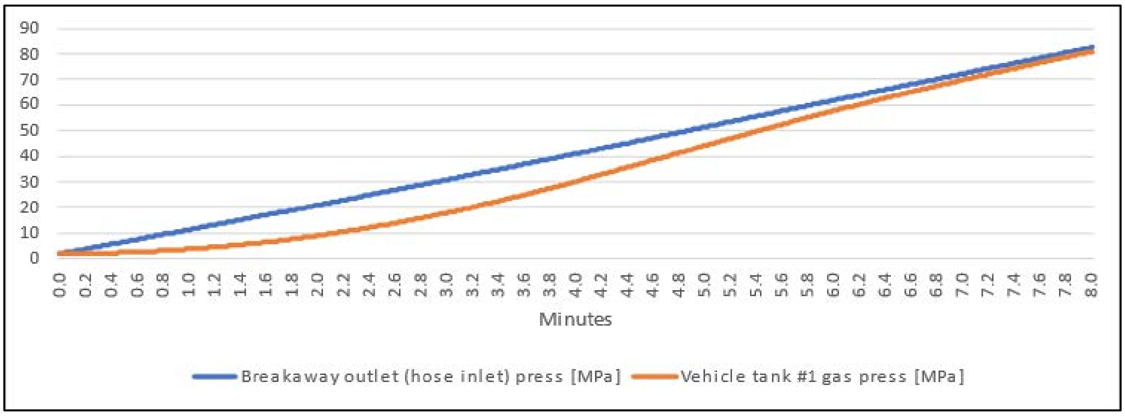


Figure 12: Dispenser to tank Pressure Drop (MPa)

The team will continue to utilize the H2Fills model over the course of the project to fine tune the dispenser and nozzle assembly hardware and component selection.

4.2 Testing

In order to determine the correct pressure drop characteristic, the team has performed several mathematical CFD analyses – not limited to the nozzle, but to the entire hose assembly and entire dispenser. Furthermore, to validate these mathematical approaches, the team has contracted a laboratory to perform an actual flow test on existing nozzle assembly and dispenser with 12 mm, even though the used components are working at lower pressure. Based on this result, it shall become possible to validate the needed ID for the final nozzle assembly and also dispenser design, which again will decide on the forces required to operate the sleeve manually.

4.3 NREL Validation

In the validation phase, other metrics like reliability of the components, ease of use for the user, and how to implement at an existing station will be studied with the new dispenser system. Upon completion of the buildout of the high-throughput dispensing system, it will be validated at NREL’s Hydrogen Infrastructure Testing and Research Facility (HITRF). NREL’s existing LD research-based hydrogen fueling station was recently upgraded for fueling HD fuel cell electric trucks as part of a federally funded/industry lead project. The station is designed with the appropriate storage capacity, compression, and cooling to perform high-throughput fills at 70 MPa, -40° C, and 10 kg/min up to 60 kg. The station includes both on-site renewable hydrogen generation by electrolysis as well as hydrogen recirculation capabilities (so that little hydrogen is wasted during testing). A HD vehicle simulator (HDVS) was also designed and built as part of this effort to run fueling tests up to 80 kg. The HDVS will include a thermal chamber to evaluate fueling at various ambient temperatures. The facility is shown in Figure 13.

Figure 13: NREL’s Hydrogen Infrastructure Testing and Research Facility

During the build phase, the research team will identify the interface requirements between the dispensing system and HITRF in order to be ready for validation testing once the system is ready. NREL will document the necessary steps for field deployment of this system by performing a Process Hazard Analysis (PHA). These steps will be completed by the research team, on the integration of the equipment within HITRF.

The HD dispenser and nozzle assembly will be integrated into the NREL HD hydrogen station near the HDVS. The HDVS will be outfitted with a receptacle and appropriate infrared communication devices. Testing will be completed by executing a variety of fueling events (appropriate to the fueling protocol standards available at the time of test) that are representative of fueling HD FCEV.

The data collected will include fill amounts, rates, temperatures, pressures, starting and ending states-of-charge, and failures. The NREL facility is an integrated proving ground for how the dispenser system could be successfully implemented at high-throughput stations. There will be optimization opportunities around the hydrogen storage, controls scheme, and number of fueling positions this dispensing system can support.

5 Appendix A: Specifications and standards

Table 8: Dispenser specifications and standards

Dispenser	**Units**	**Min**	**Max**	**Requirement**
Gas operating temperature	C	-40	65	
Dimensions				Designed to fit on typical truck fueling island
Fueling protocol				Based upon industry standard or SAE J2601 2020 CHSS D
Retail system				EMV point of sale system
Display				Point of sale; Optional - information material
Vehicle communications				IRdA Communication fueling designed to SAE J2799 with backup non-communication fill
Station & POS communications				Bennett Open Protocol - Modbus
Design standards				NFPA2 and ANSI/CSA HGV 4.1⁺, DMS, NFPA 496, CTEP, MET Labs Certification for purged and non-purged.
Products/Hoses				Up to 2 per side
Test requirements				ISO 19880-1 Section 12.5 Fueling safety and performance functional testing. CSA HGV 4.3 2021⁺ for protocol validation

⁺ Modified for HD

Table 9: Nozzle assembly specifications and standards

Nozzle Assembly	**Units**	**Min**	**Max**	**Requirement**
Kv			15	SAE J2601 2020 Section 7.2

Table 10: Breakaway specifications and standards

Breakaway	**Units**	**Min**	**Max**	**Requirement**
Weight	kg		5	
Separation force	N	222	1000	
Gas operating temperature	C	-40	65	
Connection*				9/16" - 16 UNF medium pressure female
Design standard				ISO 19880-3 2020⁺, CSA HGV 4.4 2013⁺
Testing standard				ISO 19880-3 2020⁺, CSA HGV 4.4 2013⁺

*Tentative, to be determined as part of the project ⁺ Modified for HD

Table 11: Nozzle specifications and standards

Nozzle	Units	Min	Max	Requirement
Weight	kg		4.5	
Gas operating temperature	C	-40	85	
Communications				Field replaceable IRdA system designed to SAE J2799 which is electrically classified
Disconnection time	s		30	Designed to prevent freeze lock that prevents disconnection within 30 seconds
User protection				Designed to dissipate static electricity and protect user from frostbite
Receptacle inter-compatibility				Designed to prevent connection to nozzles designed for other vehicles or other higher-pressure HD nozzles
Nozzle inter-compatibility				Designed to prevent connection to receptacles designed for other vehicles or other lower pressure h HD receptacles
Hose protection				Designed with strain relief and twisting protection for the hose
Hose connection*				13/16"-16 UNF medium pressure female for 9/16" hose
Design standard				ISO 17268 2020$^+$
Testing standard				ISO 17268 2020$^+$ except durability

*Tentative, to be determined as part of the project $^+$ Modified for HD

Table 12: Hose specifications and standards

Hose	Units	Min	Max	Requirement
Length	m	0.5	4	
Bending radius	mm	250		
Cycle life	years		2	Assuming 100 cycles per day
Design				Will consider approach to reduce hose whip
Gas operating temperature	C	-40	85	
Connection*				9/16" - 16 UNF medium pressure male
Hose protection				Include hose cover
User protection				Designed to dissipate static electricity and protect user from frostbite
Design standard				ISO 19880-5 2019$^+$
Testing standard				ISO 19880-5 2019$^+$

*Tentative, to be determined as part of the project $^+$ Modified for HD

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[1] Society of Automotive Engineers. (2020) *Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles* (SAE J2601_202005) https://www.sae.org/standards/content/j2601_202005

[2] International Organization for Standardization. (2020). *Gaseous hydrogen — Fuelling stations — Part 1: General requirements* (ISO Standard No. 19880-1:2020. https://www.iso.org/standard/71940.html