

Design, Analysis and Testing of a Low-Cost Hydrogen/Oxygen Augmented Spark Igniter for Kerosene Ignition

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A hydrogen and oxygen torch igniter provide a simple approach for igniting fuel rich kerosene propellants. However, currently few general guidelines exist for designing such type of igniter, and there is little discussion in the open literature on how to design an igniter for use in a combustion experiment besides through an experimental trial and error approach. The same trial-and-error approach resulted in hardware damage when we attempted to modify an existing torch design for a fuel rich kerosene experiment by varying test parameters complemented with a simplified zero-dimensional modeling approach. To investigate the problem, we ran a non-reacting 3-D CFD simulation of the torch igniter and identified several important design flaws that likely explain what happened during testing. Afterwards, we redesigned the torch igniter based on our findings from the initial torch design and with guidance from 2-D Axisymmetric Reacting Flow CFD. The redesigned torch igniter testing was successful and agreed with our updated models. This paper discusses our approach to designing a torch igniter, including the motivations of the design features. It also provides some insight from our analysis and experience that may be useful for designing an oxygen rich GH₂/GOx torch for similar applications.

Nomenclature

GH ₂	=	Gaseous Hydrogen
GOx	=	Gaseous Oxygen
RP-2	=	Rocket Propellant-2
m	=	Gas mass
<i>c_v</i>	=	Gas heat capacity at constant volume
T	=	Temperature
u	=	Gas internal energy
ω	=	Gas species production rate
V	=	Reactor Volume
<i>M_w</i>	=	Gas molecular weight
\dot{m}	=	Gas mass flow rate
h	=	Gas enthalpy
Y	=	Gas species mass fraction
<i>e_{ign}</i>	=	Energy input to reactor
δ	=	Unit Pulse
p	=	Gas Pressure

Subscripts

k	=	<i>k</i> th gas component
in	=	inlet to reactor
out	=	outlet from reactor

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I. Introduction

A numerical and experimental study of soot formation and deposition at rocket-like fuel rich kerosene combustion is ongoing at the Zucrow Laboratories [1–3]. As part of the study, a fuel rich combustor has been designed to enable soot deposition measurements for model comparison. The experiment consists of a liquid RP-2 and gaseous oxygen combustor, which are injected through three fuel-oxidizer-fuel triplet injectors and designed based on empirical guidelines in SP8089 [4]. The propellants are combusted in a mixing/combustion chamber and then the gases flow through a sample chamber, where carbon deposits are measured post-test, and finally out through a converging choke plate, which is used to set the chamber pressure. The operating conditions for the experiment are summarized in Table 1.

Table 1. Soot Deposit Experiment Operating Conditions

Mixture Ratio	RP-2 Flow Rate	GOx flow rate	Run Time	Chamber Pressure
1	30 g/s (0.066 lbm/s)	30 g/s (0.066 lbm/s)	6 s	250 psia
	15 g/s (0.033 lbm/s)	15 g/s (0.033 lbm/s)		500 psia
	45 g/s (0.099 lbm/s)	45 g/s (0.099 lbm/s)		750 psia
	60 g/s (0.066 lbm/s)	60 g/s (0.066 lbm/s)		250 psia
				750 psia
				500 psia

The propellants in the experiment are ignited with a GH₂ and GOx torch igniter. The torch igniter design was initially based on a hybrid of the Repas and Helderman configurations [5,6] and designed with a 0-D perfectly mixed assumption. However, testing resulted in significant hardware damage and post-test reacting flow CFD results showed that the perfectly mixed assumption is extremely erroneous. Additional CFD simulations were then used to inform design of a second torch igniter, which was repeatedly tested with no visible hardware damage. An overview of the experiment design with the redesigned torch igniter is shown in Figure 1.

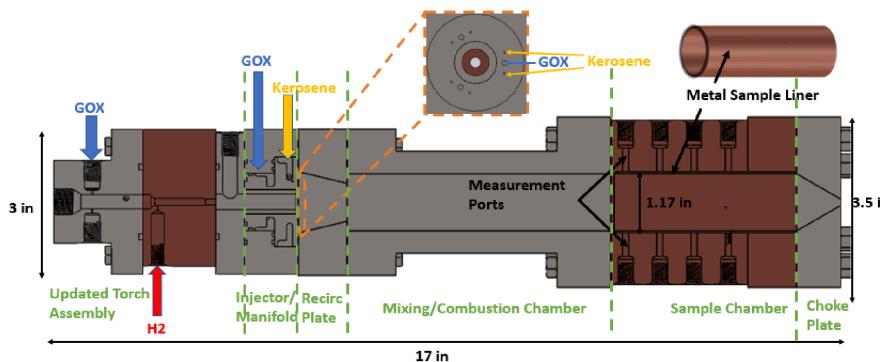


Figure 1. Soot Deposit Experiment overview with the redesigned torch igniter [Bottom]

This paper discusses the design and flaws in the initial design as well as the redesigned torch for use in the soot deposit experiment. It also provides considerations for designing a hydrogen/oxygen torch igniter based on our experience, some of which we did not find during our torch literature review.

II. Initial Design

A. Overview

Our initial torch igniter was based on the designs discussed by Repas and Helderman [5,6]. Gaseous oxygen and hydrogen were injected into the main torch chamber at a very oxidizer rich mixture ratio of ~50, like in the Repas' design. However, unlike the Repas design which uses a Champion N19 surface gap spark plug, we used a low-cost

Auburn SI-140 furnace igniter. The Auburn SI-140 igniter has been reliably used at high pressures by Helderman and other research groups at the Zucrow laboratories[7,8]. The Auburn igniter contains a center electrode and spark discharge occurs between the electrode and closest chamber surface. In our initial igniter design, we used a #5-40 screw to set the spark gap distance, which was calculated from Paschen law for oxygen [9,10]. The spark was used to ignite the propellant mixture in the main torch chamber which was then injected into the experimental combustion chamber through a center torch tube. Simultaneously, additional hydrogen gas was injected around the torch tube in a coaxial annular chamber, like in both the Repas and Helderman designs. The additional hydrogen gas produced a mixture ratio of 5 at the torch exit. The configuration is shown in Figure 2.

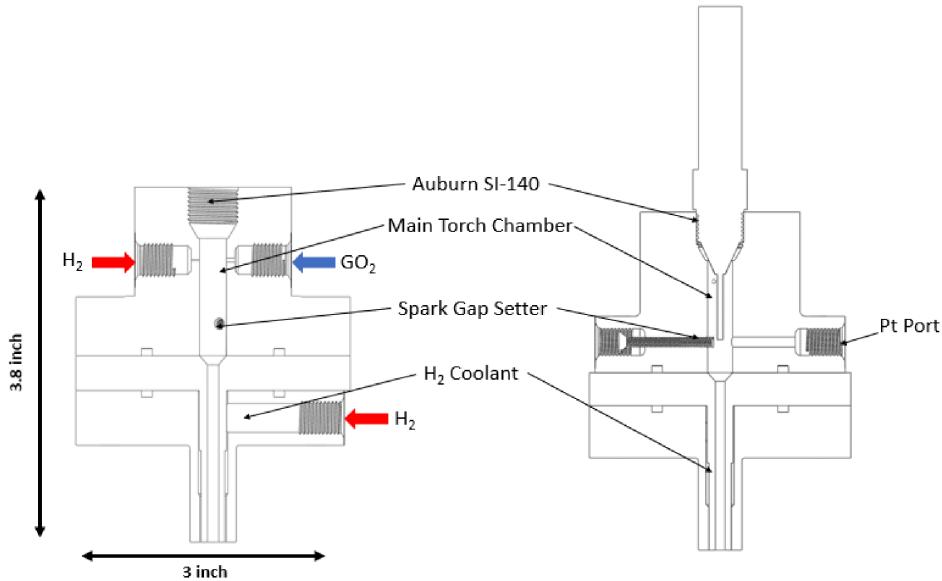


Figure 2. Initial Torch Igniter Design, consisting of a center torch chamber where GO_x/GH₂ are ignited at an Ox-rich mixture ratio and coaxial GH₂ coolant jacket. The mixture ratio at the torch exit is close to stoichiometric

In our initial design analysis, we erroneously assumed that the hydrogen and oxygen propellants in the main torch chamber are perfectly premixed, with an adiabatic equilibrium temperatures of ~2100K at a mixture ratio of 50 and design pressure of 300 psia, as calculated with the NASA CEA code [11]. Our initial heat transfer analysis showed that at this temperature and, for conservativeness, at a higher pressure than any test conditions of 1000 psia the torch should be able to operate for several seconds. As will be discussed, our later analysis showed that with this initial torch configuration at a mixture ratio of 50, the mixture is very nonhomogeneous, and the heat transfer analysis was invalid. Furthermore, we sized the torch flow rates by considering the minimum ignition energy required to ignite the kerosene and gaseous oxygen mixture at a mixture ratio of unity, corresponding to conditions required for the soot experiment. The minimum ignition energy was conservatively estimated via an adiabatic 0-D well stirred reactor (WSR) model. The model was created using the Cantera toolbox, with the standard zero-dimensional well stirred reactor equation formulation [12]. Reaction rates and thermodynamic properties were evaluated with the HyChem POSF5433 reaction mechanism [13,14]. The inlet to the reactor was set to premixed mass flow corresponding to the soot deposit experiment conditions, shown in Table 1; and the outlet mass flow calculated from the compressible 1-D choked flow relations. To calculate the minimum ignition energy, a pulse of energy was introduced at time zero with a delta function. Numerically, this was done by modifying the enthalpy of the initial inlet mixture and solving the following WSR energy formulation:

$$mc_v \frac{dT}{dt} = - \sum_k u_k (\omega_k VM_{w,k}) + \dot{m}_{in} \left((h_{in} + e_{ign} \delta(t)) - \sum_k u_k Y_{k,in} \right) - \frac{pV}{m} \dot{m}_{out} \quad (Eq\ 1)$$

The WSR was then integrated to steady state. If the input energy was too low, then the propellants would just increase in temperature but fail to ignite within the residence time of the soot experiment combustor. At some point, the energy is high enough to ignite the propellants, but the ignition delay could be long. If the energy is increased further, then the minimum residence time required to ignite the propellants decreases. In all the cases, the final steady state solution has been verified to be identical once the propellants have ignited. Once the minimum ignition energy is determined, the torch flow rate could be estimated by balancing the total minimum energy required to ignite a certain mass flow of propellants with the reaction energy of the torch (for a specific mixture ratio):

$$\dot{m}_{torch} = \frac{\dot{m}_{in} e_{ign}}{\Delta h_{rxn,OF}} \quad (Eq\ 2)$$

Calculation of the minimum ignition energy with this method is likely overly conservative since the transient mixture ratio injected into the chamber varies at startup as pressure increases in the feedlines and manifolds after the propellant run valves are opened. Non-uniform injection would also create localized regions where the mixture ratio is closer to stoichiometric and require less energy to ignite. More accurate estimates of minimum ignition energy may be determined from experimental data in literature, though none were available for our operating conditions, or via an approach such as what is described in Turns combustion textbook for calculating minimum flame kernel radius to produce ignition [15]. However, since accurately determining the ignition energy was not important for our work, as long as the propellant ignites, we went with this approach. The resulting total torch flow rate was set to 15 g/s (which was about 56% higher than minimum calculated ignition energy and even more conservative). The breakdown of the chamber and coolant flow rates is summarized in Table 2.

Table 2. Initial Torch Igniter Flow Rates

Flow	Mixture Ratio	Flow Rate [g/s]
Torch O ₂	50	12.5
Torch H ₂		0.25
Coolant H ₂	0	2.25
Combined Flow	5	15

Another aspect of the torch design and incorporation into the main chamber taken into consideration was the valve sequence, including purge flow timing. To guide design of the valve and purge timing sequence, we built an object-oriented well stirred reactor network model using the Cantera toolbox [12] for the torch, main chamber and feed-system. The network consists of well-stirred reactor nodes that are connected to other well-stirred reactor or constant property pressure reservoirs. Each reactor in the network is modeled as an ideal gas reactor, where the density is calculated from the ideal gas equation of state. The flow in between the reactors is controlled via a Cantera Mass Flow Controller object, where the mass flow is calculated from compressible flow equations. Each fluid line segment in the experimental feed-system was modeled as a zero-dimensional well-stirred reactor. An overview of the model is shown in Figure 3, and the torch fluid system plumbing diagram shown in Figure 4.

With this model, we explored several torch operating conditions and feed system configurations for running the main soot experiment. The hot torch flow can affect the steady state measurements in the main soot experiment if it is on for the entire experiment duration. As such, we explored options for safely turning the torch off after ignition of the main propellants. An initial approach we considered was having the torch hydrogen and oxygen feed pressures be below the ignited main chamber pressure, with check valves at the manifold inlets preventing backflow into the feed lines. The torch would then effectively shut off during ignition. However, it was deemed that check valves were not a robust enough engineering control to prevent the possibility of chamber gases backflowing into the torch oxygen lines. So, with safety in mind, the torch feed pressures were set above the maximum chamber pressure. Torch flow would only then be shut off once the torch propellant run valves are closed. Nitrogen purge flow, plumbed to the run lines, as shown in Figure 4, would be on during the entire test sequence and set to a higher pressure than the maximum chamber pressure to prevent backflow and keep the propellant lines clean. The purge pressure was set to be above the

maximum chamber pressure but below the torch hydrogen and oxygen feed pressures. A check valve was installed downstream of the purge valve to shutoff purge flow whenever the torch propellants were flowing, as shown in Figure 4. This also added some extra safety by having the purge valve remain open and nitrogen ready to flow during abort.

It should be noted that one issue with this feed system configuration, which was not necessarily important for our soot experiment but should be considered for other applications, is the purge flow can contribute to a considerable amount of the total combustor flow and affect combustion performance. The torch hydrogen and GOx injector areas were partly sized with this consideration in mind. For both injectors, it was desirable to have a smaller injector hole diameter in order to limit the amount of purge flow into the combustor. However, at the same time, a smaller injector hole requires a larger feed pressure in order to deliver the design mass flow rate. After iterating on the injector and feed system, we settled on a GOx injector hole diameter of 0.05 inch since it would allow us to minimize both the required upstream pressure and purge flow. For hydrogen, even though the density is 16 times smaller than GOx, the design flowrate was smaller by a factor of 50 and this allowed using a smaller injection hole. However, the hole diameter was limited to 0.02 inch primarily because this is the smallest that could be machined, at least economically. A smaller diameter orifice was installed into the torch chamber in order to have a high enough upstream pressure at the design mass flow rate.

The plumbing and instrumentation diagram for the torch igniter setup is shown in Figure 4. Predictions of system pressures, with the model shown in Figure 3, for one of the conditions of the soot experiment are shown in Figure 5. The valve timing was iterated in the model until a sequence was found that produced successful ignition without backflow and pressure spikes, at least numerically. In this sequence, the torch purges are initially turned on, which results in pressure building up in the GOx and hydrogen feed lines. Afterwards, GOx is turned on followed by hydrogen 0.2 seconds later. Ignition is calculated to occur around 1 second, when the mixture reaches an ignitable ratio. Afterwards, main RP-2 and GOx are injected, which results in a pressure rising above the steady state design pressure because of torch flow. The GOx and hydrogen valves are then turned off and the chamber pressure drops to the design pressure. At the same, there is some pressure drop across the GOx and Hydrogen feed lines, which should prevent backflow. The hydrogen manifold pressure drop is a lot smaller and may experience backflow, because a smaller injector diameter could not be machined, but for our experiment this should not be an issue and will be cleaned after every test.

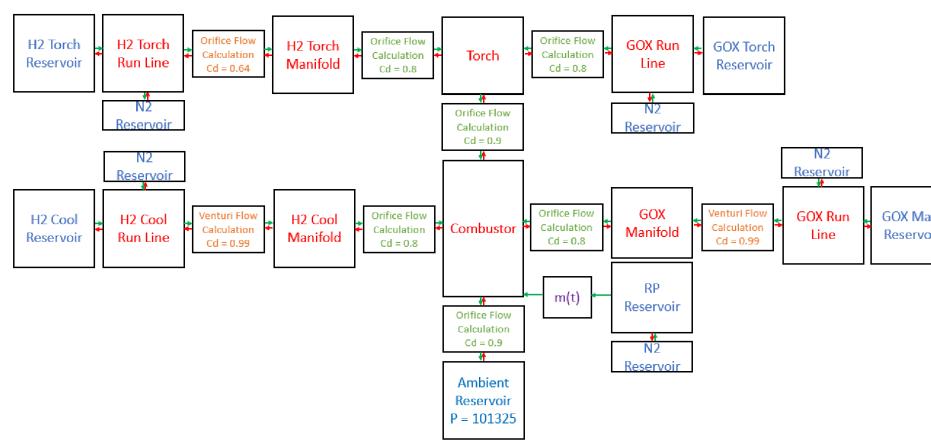


Figure 3. Reacting Engine Systems Model Overview. Red components are well stirred reactors, where transient temperature, pressure and species mass fractions are solved; blue components are reservoirs, where temperature, pressure and species fractions are static; and green and orange are mass flow controllers that govern mass flow between the reactors. The green arrows are upstream flow and red are downstream flow.

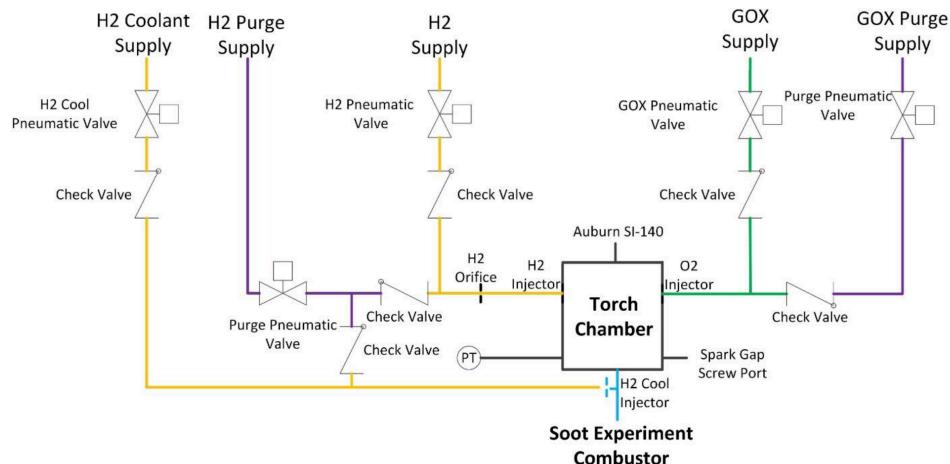


Figure 4. Torch Plumbing and Instrumentation Diagram

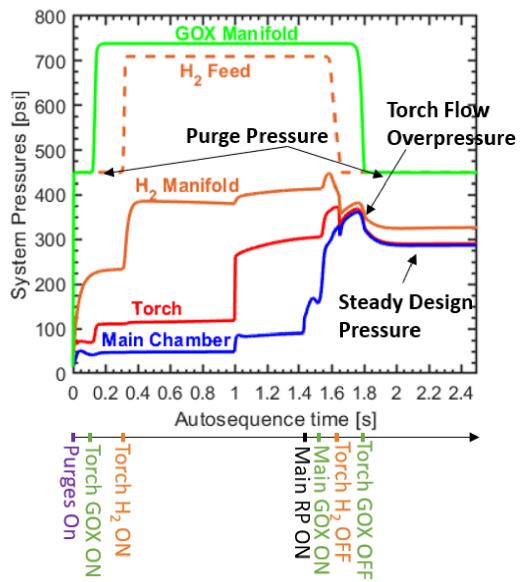


Figure 5. Predicted Torch System Pressures during operation in the soot experiment

B. Torch Component Testing

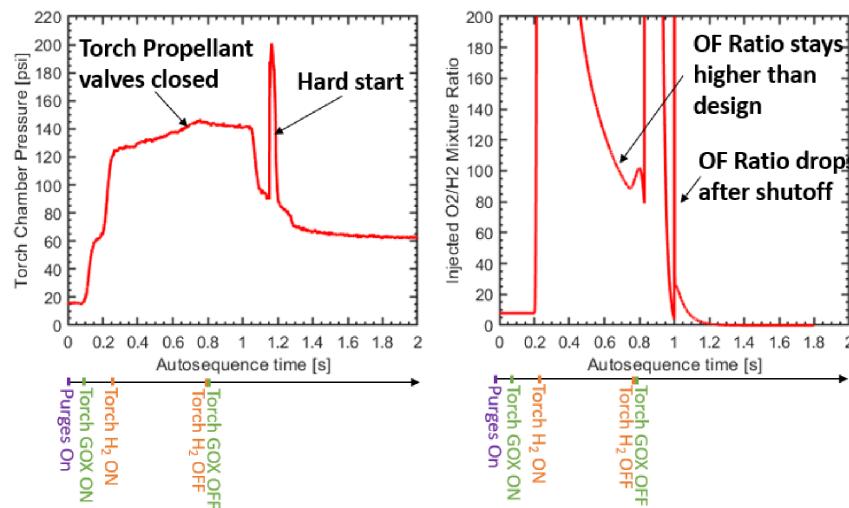
The first test campaigns involved the torch igniter without the soot experiment combustion and sample chambers. We also only tested with GOx and torch chamber H₂ flow. Nitrogen was flown in the annular coolant jacket around the torch tube. The operating conditions for all the torch tests that we ran are shown in Table 3. The GOx flow rate was set by the injector, as described in the previous section, and the H₂ flow was set by a McMaster orifice.

Table 3. Torch Test Operating Conditions

Flow	Mixture Ratio	Flow Rate [g/s]	Orifice Diameter [inch]	Propellant Supply Pressure [psia]	Purge Pressure [psia]
Torch O ₂	50	~12.5	0.05	740	400
Torch H ₂		~0.25	0.016	710	350

Before hot-fire testing, we cold-flowed with nitrogen to characterize the transient response of the feed system and to get a rough estimate of the discharge coefficients. This involved measuring the torch chamber pressure response after both separately and simultaneously opening each individual run line at several supply pressures. From this data, we back calculated the discharge coefficients of the GOx and H₂ injectors, as well as the H₂ orifice and the torch tube. It also provided a rough estimate of the valve opening time. These parameters were used in the well stirred reactor systems model, shown in Figure 3.

In the subsequent hot-fire tests, the spark was on for the entire duration, purge valves were initially open, and the GOx valve was opened with a 0.2 second lead before hydrogen in order to prevent the chamber mixture ratio from dropping below the design mixture ratio of 50 during startup. Since the purge valves were open initially, the run lines and chamber filled with nitrogen. As a result, after opening the run valves the propellant gases in the lines were initially dilute and required some time for the propellant mass fraction to build up. In turn, the gas composition in the torch chamber took some time to reach an ignitable mixture ratio, as calculated and shown on the right of Figure 6. Our first tests had the GOx run valve open for a short duration, less than 0.3 second, and these failed to ignite because the torch gas composition had not yet reached an ignitable mixture ratio. However, after doubling the valve run duration, we encountered an issue where the igniter still did not ignite while the propellant run valves were open but produced a hard start about half a second after the valves were closed before being extinguished by the purge flow.. The chamber pressure reading on the left of Figure 6 shows this behavior during one of our tests. We traced this issue to the transients in the fluid system. As mentioned, it takes some time for the nitrogen in the fluid lines to evacuate and to fill with the propellant gas. The time required was longer than our initial run sequence. At shutdown, the hydrogen run valve closed 0.1 second before the GOx valve. However, the hydrogen flowrate was significantly smaller than the oxygen flowrate and in turn the rate at which the residual hydrogen in the line was emptied was smaller than GOx. As a result, the injected mixture ratio from the residual gas in the lines dropped, as shown in our calculations on the right of Figure 6. A smaller residual gas mixture ratio would have been easier to ignite hence was likely the cause of the hard start.

**Figure 6. Measured Chamber Pressure [Left] and Calculated Chamber Mixture Ratio [Right] for a torch test that produced a hard-start ignition after run valves were closed**

After tracing the initial problems to the run sequence, we tried two additional tests in an attempt to get successful and smooth ignition. The first approach simply involved running the same sequence for a longer time. This initially produced a relatively smooth ignition. However, there was still a pressure spike near shutdown and damage to the Auburn SI-140 ceramic, in addition to some melting of the electrode near the hydrogen injector as shown on the left of Figure 7. Our initial thought was this problem was still due to mixture ratio near the hydrogen injector dropping during the shutdown transient and causing the observed damage. As a remedy, for the next test we had GOx run valve open for 2 seconds and essentially purging the chamber with GOx before injecting the nitrogen purge. However, this test resulted in significant hardware damage. There was a smooth ignition at start, but the chamber pressure continued to rise after hydrogen was turned off. After the nitrogen purges finally kicked in, we noticed the chamber pressure reading was much smaller than nominal, which indicated that the torch tube outlet area had enlarged. In reality, the torch tube had completely burned up. The nickel electrode was also mostly completely vaporized, except for about a quarter of an inch from the top, as shown on the right of Figure 7. The chamber though was intact with little signs of thermal damage, and the coolant jacket was also largely intact, likely saved by the purge flow that was running. No further testing was done with this torch configuration, as the results clearly showed a problem with this torch configuration.

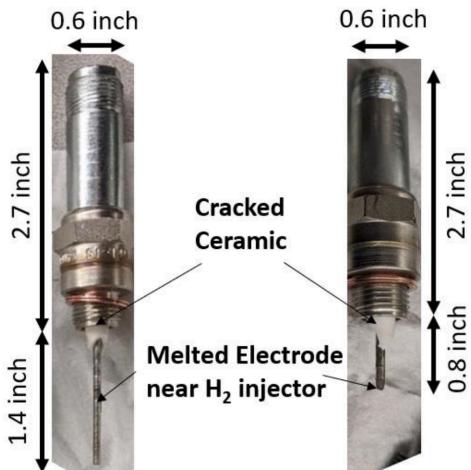


Figure 7. Post-test inspection of the Auburn SI-140 electrode for the second to last test [Left] and the last test [Right]

C. Post-test analysis

The test results showed there was an issue with the torch design. However, it was not entirely clear from the test data and the 0-D model what the cause of the hard-start was and what lead to experimental hardware damage. The nickel electrode was almost completely vaporized so this suggested that the temperatures in the torch chamber were significantly higher than predicted. We originally thought the issue might have been due to the shutdown transient, but the last test seemed to confirm that this was not the case. It was thought that a local hotspot near the hydrogen injector could have led to some initial melting of the electrode, followed by the nickel metal itself burning in the oxygen rich environment. However, this behavior could not be captured with our 0-D model, so we ran a non-reacting 3-D CFD simulation of the torch chamber to get an idea of the conditions near the hydrogen injector.

The CFD calculations were done with the General Equations and Mesh Solver with Multiple Approaches (GEMSMA) CFD code, which was developed over a 20 year period by Professor Merkle's research group at UTSC and Purdue University [16]. GEMSMA has previously been used to analyze problems including combustion instability, hypergolic propellant modeling, and rotating detonation engines [16–18]. GEMSMA is a finite-volume density-based solver that computes time accurate, coupled solutions of the multi-species reacting flow Reynolds Averaged Navier Stokes governing equations, along with the continuity, species transport and energy equations. The equations in this work were discretized with second order spatial and temporal accuracy. The cell interface fluxes

were calculated via the Roe scheme. Wilcox's $k-\omega$ turbulence model [19] was used for turbulent closure. The equation of state for this work was ideal gas. The thermodynamic and transport properties for each species were calculated based on the NASA piecewise polynomial functions that is described by McBride et al. [20]. Viscosity and thermal conductivity curves were generated for each species as a function of temperature from the Chemkin thermodynamic and transport data, as described in the Chemkin manual [21]. These curves were then fit by least squares to the NASA polynomial function. Mixture properties for viscosity, thermal conductivity, and mass diffusivity were calculated via the mixing rules of Bird and Mathur [22,23]. The equations, along with source terms, were solved implicitly via the line Gauss-Seidel algorithm. Further details about the numerical schemes are provided in Dr. Harvazinski's PhD Dissertation [16].

The 3-D simulations were run with roughly 5 million computational cells, with a time step of 10^{-5} seconds on the Purdue Brown RCAC cluster. No mesh or time step sensitivity studies were done since we were primarily interested in a rough qualitative prediction of the mixture near the hydrogen injector. But we ensured the y^+ value at the wall boundaries was in the range of 0.75-1.5 inch order to properly capture the turbulent wall effect with the $k-\omega$ turbulence model. We also slightly simplified the geometry and didn't model the fluid flow geometry that feeds into the torch injector. Instead we assumed a constant steady uniform mass flow at the hydrogen and oxygen injectors, corresponding to the torch test operating conditions shown in

Figure 2. The torch tube was also not modeled and instead the torch exit area was set to an ambient pressure condition. The modeling domain and boundary conditions are shown in Figure 8.

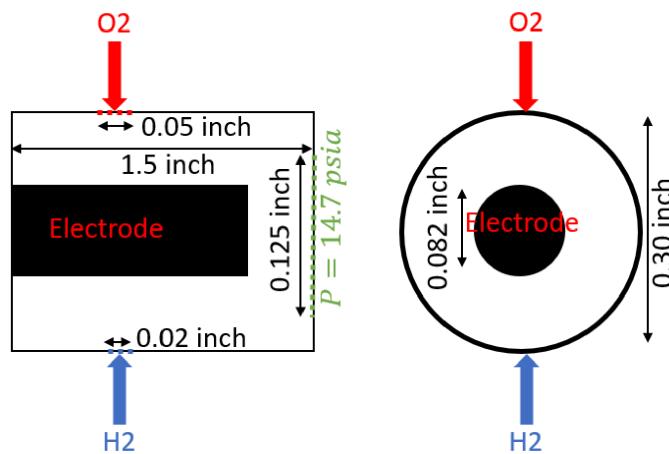


Figure 8. Non-reacting 3-D CFD model setup of the torch igniter chamber. The torch tube was not modeled and instead a uniform outlet pressure assumed at the exit.

The resulting simulations were run until steady state. We were not able to get mass flow convergence between the inlets and exits because of a large amount of recirculation within the domain. However, we ran the simulation until the temperature, pressure and mass fraction solution at several point probes within the domain reached a limit cycle. The results of the simulation are shown in Figure 9.

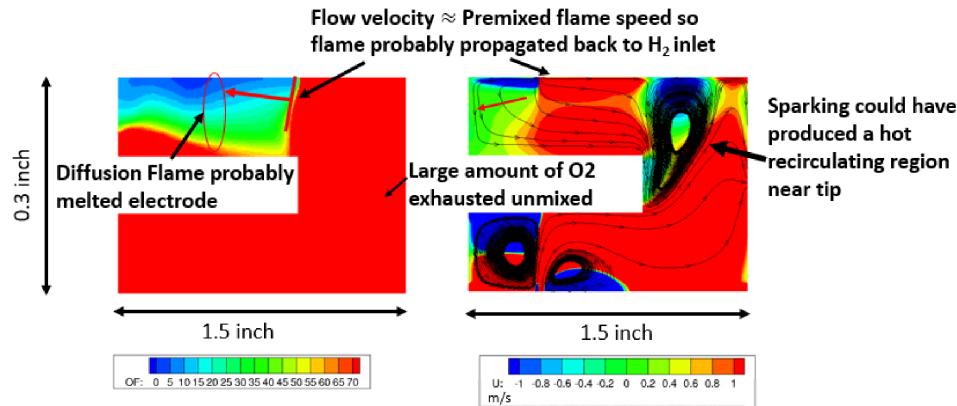


Figure 9. Non-reacting CFD results O_2/H_2 Mixture Ratio [Left] and Velocity [Right] for the initial torch igniter

The non-reacting CFD results suggest what may have led to the failure of the torch and show several clear pitfalls with the initial torch design. The zero-dimensional analysis, that we originally used to design the torch, assumed perfect mixing within the torch chamber, with a uniform mixture ratio throughout the domain. However, as the left of Figure 9 shows, this was an extremely poor assumption. The large oxygen to hydrogen flow rates, at a mixture ratio of 50, essentially resulted in oxygen filling the chamber. The injected hydrogen velocity in this design is also small, and hence the injected hydrogen momentum is small, which essentially resulted in hydrogen being pushed closer to the injector. Mixing occurred primarily via diffusion, not very efficiently, and the results show this would have produced nonhomogeneous mixture ratio in the chamber. There was also a large amount of oxygen that was exhausted unmixed. About 70% of the cells near the outlet area had oxygen mass fraction of unity.

Furthermore, due to the large difference in the momentum ratio of the injected hydrogen to oxygen, the results predict a recirculating region may have formed near the electrode tip. The recirculation would have occurred near where the sparking was occurring. We did not model sparking, but it is probable that this region may have been substantially heated. As a result, when the mixture ratio became favorable for ignition, it likely would have ignited in this region. This could explain why in our initial tests we observed ignition about 0.5 second after the sparking and run valves were closed. As the residual hydrogen in the lines flowed out, the mixture ratio could have continued to drop in this region and even though the spark was turned off, this recirculating region could have been hot enough to produce ignition. The hydrogen could have also pooled up near the torch, and since the gas velocity in this region was very small, a flame near the ignition region could have rapidly propagated upstream to the hydrogen injector. Rapid consumption of hydrogen in the region may have led to the observed pressure spikes in all, except the last, test conditions. In the case, where we ran with hydrogen and oxygen valves open for a longer period, hydrogen would have still been flowing after the flame propagated to the injector. Since the injection velocity would still have been small, a diffusion flame would have formed in the surrounding oxygen rich environment. The diffusion flame would have then impinged on the electrode surface causing it to melt, as we observed in our last two tests. The last test was especially dangerous, since now if the diffusion flame was melting and started burning the nickel electrode, then the oxygen would have supported the combustion after hydrogen was turned off. The electrode burning would have resulted in significantly higher heat fluxes than what the torch was designed to handle and hence was probably responsible for the melting of the torch tube.

In summary, the experimental and CFD results suggest that a Repas-like torch igniter with a center electrode is an extremely poor design choice. The original Repas igniter uses a surface sparkplug, with no center rod onto which a potential diffusion flame could impinge. Hence, the Repas igniter would likely have worked with our operating conditions if a surface sparkplug was used instead. However, it's not in the Repas paper, but since the flow in the torch chamber is also relatively stagnant, there might still be a risk of a hard-start if the hydrogen gas builds up and then suddenly ignites. The Repas igniter used an aerospace grade Champion spark-plug which could likely tolerate the hard-start; however, the cost is significantly higher than the Auburn SI-140's used in our igniter.