Ammonia – It's Transformation and Effective Utilization

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    In practical use, ammonia (NH_3) can be burned directly in internal combustion (IC), diesel or Stirling engines. However, because NH_3 has such a low flame temperature and is hard to ignite, it has generally not been widely used in these applications. Because NH_3 can be easily reformed into hydrogen (H_2), and as part of the effort to examine the benefits of ammonia for terrestrial applications, we develop processes for catalytic reformation of NH_3 and utilize microfibrous materials to encapsulate reforming catalyst. After demonstrating reformation of NH_3 studies were conducted on the stability and feasibility of burning NH_3 by itself and burning NH_3 with synthetic reformate. Favorable conditions for flame stability of combustion of hydrogen reformed from ammonia through this catalyst-impregnated microfibrous porous media were obtained and the results are presented. Initial findings demonstrated stable catalytic combustion and flame temperatures of 940ºC were obtained.

Nomenclature

ε	=	energy density
f	=	flow rate
Q_b	=	Heat capacity of burner

I.   Introduction

ANHIDROUS ammonia has many desirable features: it is easily storable with high hydrogen content (17.6%) and as a result it is safely transportable. Anhydrous ammonia is widely used as a direct-application fertilizer in agriculture. Today, much of the world's ammonia is made using the Haber-Bosch process with methane as a feedstock. In fact, the U.S. production of ammonia has been decreasing steadily over the past decade. On the other hand, ammonia can be synthesized from sunshine, water and air. This process does not use fossil fuels such as CH_4 or other carbon sources and thus it eliminates the production of greenhouse gases such as CO_2. In practical use, NH_3 can be burned directly in internal combustion (IC), diesel or Stirling engines. However, because NH_3 has such a low flame temperature and is hard to ignite, it has generally not been widely used in these applications. Because NH_3 can be easily reformed into H_2, and as part of the effort to examine the benefits of ammonia for terrestrial applications, our first step was to: develop processes for catalytic reformation of NH_3 and utilize microfibrous materials to encapsulate reforming catalyst. After demonstrating reformation of NH_3 studies were conducted on the stability and feasibility of burning NH_3 by itself and burning NH_3 with synthetic reformate. Given success at that point, we demonstrate an NH_3 catalytic burner. Microfibrous materials provide for the mechanical and electrical entrapment of

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a particle or fibrous solid within sinter-locked networks of a secondary fibrous matrix. A major attribute of using microfibrous materials is that the volume loading of each phase is relatively independent of the other phase, and is adjustable over a wide range compared to current state of the art materials and practices. It is based on a simple, paper-making process and reel-to-reel fabrication at substantial volume. One of the additional benefits of this process is that multiple materials/material combinations can be utilized. Materials include: polymers, ceramics and metals such as: Ni, stainless steels, Ti, Hastelloy, Nicrome, FeCrAl, and Cu. Fiber size and length options include: size: 1-50 µm; tow or chopped (1mm – 25 mm) and the matrix (after sinter bonding can include catalysts, sorbents, etc. With this process we are able to independently control material properties and even create tailored 3-D structures.

For this project a catalyst bed was prepared by the wet-lay process. It included: cellulose, 4 & 8 µm Ni fibers and 150-250 micron alumina powder. Two layers were placed on a 120 mesh stainless steel screen and sintered in H_2 at 1000°C. Chloroplatinic acid (8%) used for a loading of 10.8 wt % Pt on the alumina. The matrix was dried at 110°C and then calcined in air at 400°C. Favorable conditions for flame stability of combustion of hydrogen reformed from ammonia through this catalyst-impregnated microfibrous porous media were obtained and the results will be presented. Initial findings demonstrated stable catalytic combustion and flame temperatures of 940ºC were obtained. The feasibility of ignition and combustion of ammonia depends on: the temperature of the catalyst bed, the porosity and pore size of microfibrous media and the flow rates of NH_3 and air. As part of the project, we also operated a free-piston Stirling engine (FPSE) on H_2, with a demonstration with reformed NH_3 to follow. Stirling engines are important because they require an external source of heat and can operate over a wide input temperature ranges while maintaining their efficiency. They have been operated using propane, butane, gasoline, diesel, H_2, NH_3, solar, geothermal, nuclear and even wood as the source of heat. Selected results will also be presented.
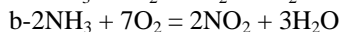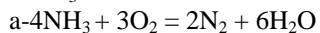
II. Ammonia Combustion

Hydrogen has lately been given attention for its high energy carrier capabilities in systems like fuel cells and other applications. However the efficiency and safety for storage and transportation of hydrogen is always an issue. Most research is focused on the metal hydrides and the so-called complex hydrides which have promising properties, but most suffer from a low hydrogen density or too slow kinetics.

The most exciting aspect of hydrogen energy is that when it is burned, it simply recombines with the oxygen in the air to create water. There are no emissions of carbon dioxide or other environmentally damaging gases. Hydrogen power has the potential to be the cleanest form of energy developed by humans[1].

On the other hand, ammonia has great potential as a hydrogen rich fuel and, with 18% of hydrogen in weight, it is a good hydrogen carrier. Since an optimized reformation catalyst for ammonia exists, it is possible to easily convert it to hydrogen. Delivery of hydrogen at a broad range of temperatures can be achieved by storing ammonia with the reformation catalyst. The reverse ammonia synthesis or "reforming" of ammonia into hydrogen and nitrogen is well understood and can be done from temperature levels close to 650K, as noted in Ref. 2. All these characteristics can be taken advantage of in systems like the Free Piston Stirling Engine Converter. On the other hand, ammonia is very corrosive and toxic, thus requiring special equipment and safety precautions when handling it.

Table I.   Estimation of flame temperatures for H_2 and NH_3 oxidation[3].

		flame temperature (Kelvin)	
Fuel	Oxidant	Calculated	Software validation (HSC3)
H_2	O_2	4,352.4	4,720.3
H_2	air	2,251.0	2,250
[a]NH_3	O_2	3,381.7	3,504.5
[a]NH_3	air	1,843.0	1,833.5
[b]NH_3	O_2	2,324.7	2,366.5
[b]NH_3	air	1035.5	938.6

a-$4NH_3 + 3O_2 = 2N_2 + 6H_2O$
b-$2NH_3 + 7O_2 = 2NO_2 + 3H_2O$

Flame temperatures for hydrogen and ammonia oxidation were calculated and then validated with a software, the results are shown in Table I. Here the next assumptions in the presented combustion analysis, are made:

   a) Both fuel and oxidant are at standard inlet combustion conditions of 298 [K] and 1 atm of absolute pressure.
   b) Combustion is complete and with no heat loss.

It was necessary to take into consideration the combustion limits for ammonia, which only burns at 15.5% to 27% by volume in air. This along other some useful data, are shown in Table II.

Table II. Ammonia Properties.

Spontaneous Ignition temperature (in air)	651°C
Flammability Limits (Vol % in air)	15.5-27
Effective Energy Density	3.5 kWhr/L
Molecular Weight	17.03
Specific Gravity NH_3 Liquid @ 68°F (20°C), 1 atm	0.6819
Density NH_3 Liquid @ -28.17°F (-33.43°C), 1 atm	42.57 lb/cu ft (681.91 kg/m3)
Density NH_3 Vapor @ -28.17°F, 1 atm	0.0555 lb/cu ft (0.8890 kg/m3)
Boiling Point	-28°F
Specific Heat	1.12 Btu/lb-°F (1.099 @ 32°F)
Latent Heat NH_3 Liquid @ -28.17°F (-33.43°C)	589.3 Btu/lb

The enthalpy of combustion is used to calculate the flame temperatures and is given by the difference between the reactants enthalpy value minus the combustion products enthalpy value at the standard reference temperature, which is 298K. When the reactants enthalpy value is equal to the combustion products enthalpy value, one can calculate the combustion products flame temperature (adiabatic temperature).

Nitrogen oxides can be formed in the combustion of ammonia. To investigate the possibility of the formation of nitrogen oxides a complex reaction equilibrium computation[4] was carried out. The adiabatic flame temperature for ammonia combustion to form nitrogen and water was computed for different amounts of excess air. Then the flame temperatures and amounts of ammonia, oxygen and nitrogen were input to the simultaneous reaction equilibrium computation for each case. Data for the enthalpy of formation, Gibbs' free energy of formation, and heat capacities were taken from a compilation in a textbook[5]. The Gibbs' free energy was extrapolated a two step integration given by Smith and Van Ness[6].

The results for adiabatic flame temperature and concentrations of NO and NO_2 are shown in Figure 1. The equilibrium levels of NO and NO_2 are in the ppm range, so they could not have an appreciable effect on the energy produced by ammonia combustion. Also, the lower flammability limit for ammonia combustion in air (15.5%) corresponds to about 50% excess air, so combustion with the higher amounts of excess air could not be sustained. The higher amounts of excess air produce lower adiabatic flame temperatures and lower amounts of nitrogen oxides.

Then it was assumed an energy density of 500W (at 30% efficiency of the FPSE) for the 2" Dia. metal porous disc burner, based on that, the flow rates were determined for several cases. The calculated adiabatic flame temperature as a function of burner efficiency for the case of hydrogen combustion is depicted in the plot of Figure 2.
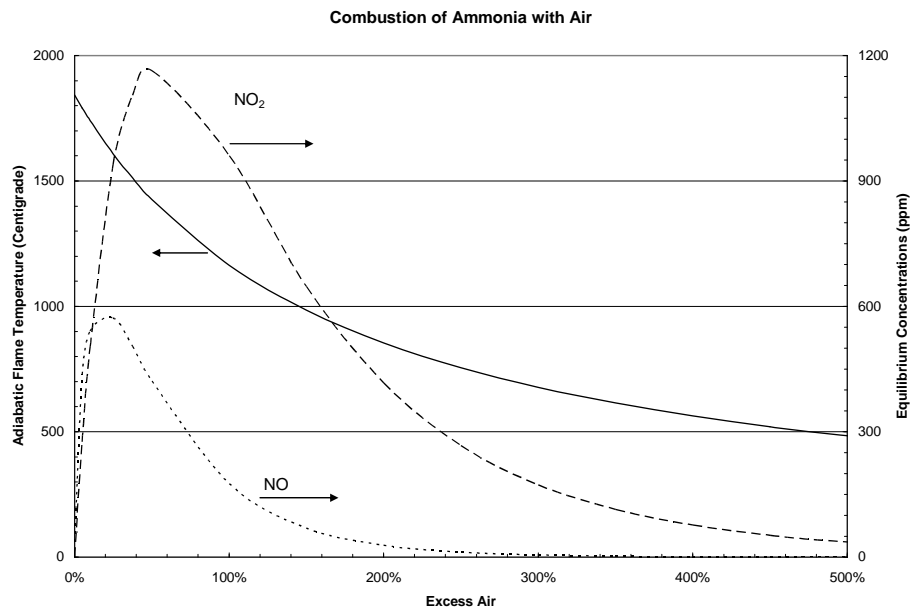

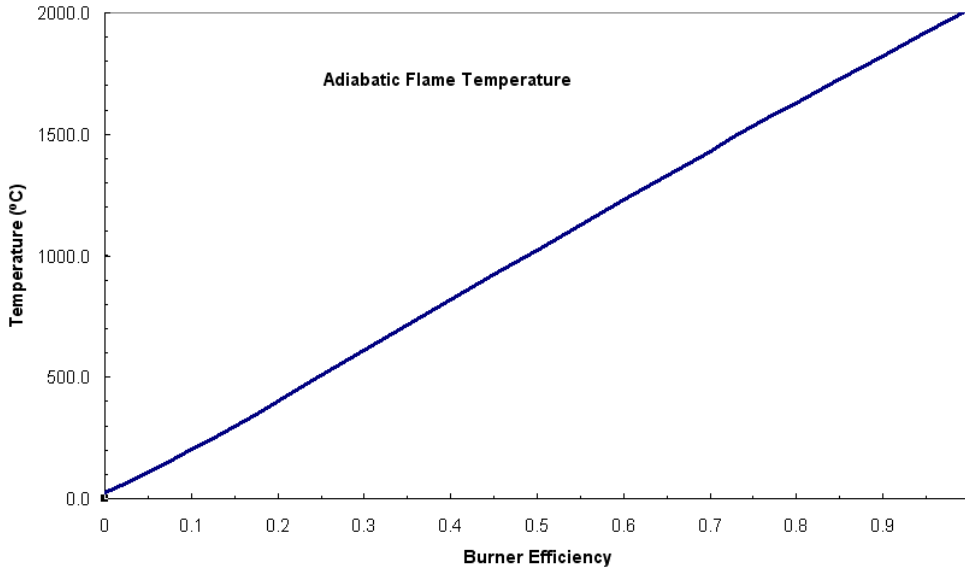**Figure 1. Reaction equilibrium for ammonia combustion with different amounts of excess air.**

Figure 2. Adiabatic flame temperature for combustion of hydrogen with stoichiometric amount of air.

III. Ammonia Decomposition

A. Burner Tests

Several tests for ammonia decomposition were done. The goal of these tests was to find out how the behavior of burning ammonia at different air to fuel concentrations through a metallic-filled porous disc, which in the future would be substituted with a similarly constructed micro-reactor to reform hydrogen from ammonia. Air was simulated by mixing oxygen and nitrogen, in this way a better control of mixing ratios was obtained. Also hydrogen was premixed with ammonia in order to find the lower and upper ammonia-hydrogen concentrations to sustain combustion at normal atmospheric conditions, which in turn would be the valid ammonia decomposition ratio for obtaining hydrogen as the ultimate energy carrier to be used as a heat source in a Free Piston Stirling Converter.

Several mass flow-meters, valves and controllers were used in the implementation of the setup test for controlling the amounts of nitrogen, oxygen, hydrogen and ammonia, Figure 3.
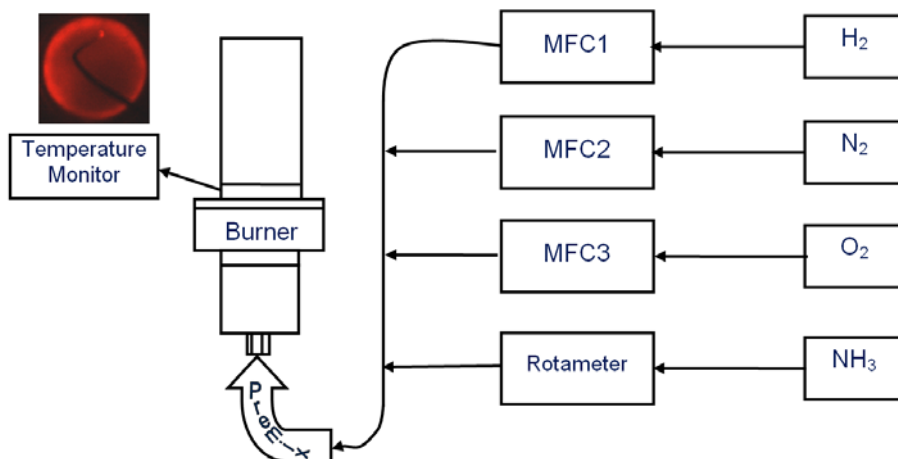

Figure 3. Schematics of preliminary burner tests done by implementing synthesized hydrogen reforming from ammonia

The first set of tests consisted on premixing different ratios of nitrogen, oxygen and hydrogen and ammonia then carry out the combustion of the mixed gases in the burner unit in normal right-side-up position. The ammonia mixture, however was difficult to burn, the flame remained just a few of seconds and then extinguished. As it can be

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observed in Figure 4 the burner is placed upside-down. In that way better stability of the flame was obtained during all tests. Previously to the tests it was necessary to make some instruments calibrations, for example, one of the flow mass controllers had a special calibration for 95% nitrogen 5% carbon monoxide, and the equivalent reading for the corresponding new gas had to be determined.

An initial preliminary experiment was run using the cylindrical burner with a metal porous media between a premixer chamber and the combustion chamber flowing hydrogen between 1 to 2 Liters per minute (LPM) and burned with external air (per 2" diameter metal porous disc). When the flow of hydrogen was turned up to 50 - 100 LPM, the flame shot up about 12 inches. Mixtures of hydrogen and oxygen without nitrogen are very explosive, even with nitrogen present care must be exercised. A rotameter was used to measure the ammonia flow and a thermocouple was used as a temperature probe to measure the flame temperature in the burner chamber.
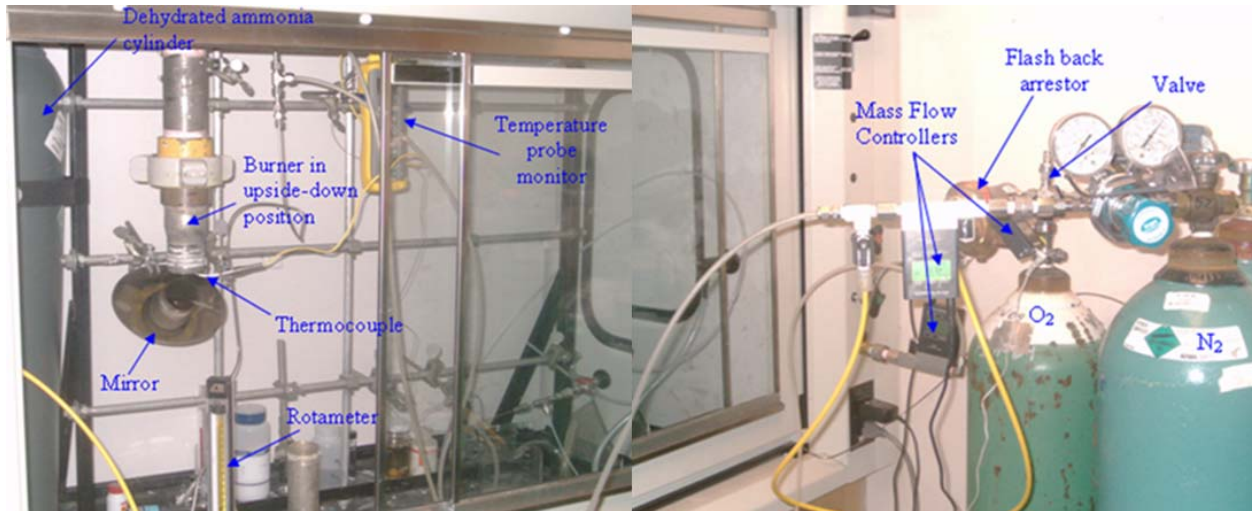

Figure 4. Experimental setup

The flow ratios were calculated for reforming hydrogen from ammonia and producing the assumed energy density of 500 Watts, as shown in Table III.

Table III. Flow ratios for producing 500W

Flow	LPM	SCFH
NH_3	4.15	8.8
N_2	20.5	43.44
O_2	4.39	9.3
H_2	8.792	18.3

For a hydrogen-only experiment, assuming 100W (20%) of the total energy density, the calculated flow rates were: nitrogen 4.1 LPM, oxygen 0.872 LPM, hydrogen 1.758 LPM, a stable flame was obtained with a temperature around 670ºC.

For the case of simulation of ammonia decomposition and hydrogen-reforming, anhydrous ammonia should be mixed with hydrogen. To this regard, several mixtures/flow rates were tested. During combustion, a large amount of the reactants' chemical energy gets released in the form of thermal energy. Ideally, all that energy is the same that should be used as a heat source for the FPSE converter.

A piece of wire mesh reinforcement was placed at the porous disc area to prevent bulging when supplying the fuel-oxidizer mixture, and contributing for a more evenly burning area. The burner was continued in upside-down position, in order to facilitate the combustion of ammonia, which in previous tests showed difficulty to sustain over a long period.

The flow rates used in the second round of tests for producing 100W (30% efficiency) were from 50% to 80% of NH_3 and 20% to 50% of H_2. With exception of one test with excess air all other resulted in a stable flame during all test long. As suggested by results, the excess air cooled out the mixture inhibiting the flame propagation, depending on the flow rate, it reduced considerably the flame temperature or even made difficult to burn the fuel-air mixture. More testing continued with excess air, and found 0% decomposition or ammonia-only (no hydrogen) burning between 0.8LPM and 1.45LPM, and a maximum temperature of 860ºC. When ammonia was turned down for excess oxygen, a temperature of 770º was observed. With no air excess a reaction temperature of 825ºC was reached.
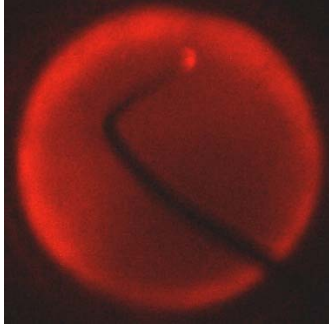
Figure 5. Flame and temperature probe inside the ring pattern formed in the burner chamber.

For the 35We FPSE it is necessary to have a heat source of about 200W, thus this value was considered for the remaining tests. The long combustion chamber was maintained and the resulting flame during this third set of tests was very stable, showing a ring pattern along the walls of the inner cylinder in the combustion chamber, Figure 5. It was noticed that the temperature along this ring was relatively higher than at the center of the cylinder. Then the temperature measurements were taken with the probe along that region. Again, several flow rates and mixtures were tested for this energy level.

Once the favorable conditions for flame stability were determined, some tests were repeated with the burner again right-side-up, for example, in conditions on tests with ammonia/H_2 ratios of 80/20, 90/10 and 100/0, flame temperatures of 670ºC, 712ºC and 770ºC were obtained respectively. It was possible to sustain a flame for several reforming percentages. Two more tests were carried out for higher power densities, for 300W a temperature of 920ºC was obtained and for 500W the maximum temperature reached was 1020ºC.

B. Ammonia decomposition Tests

After the preliminary burner tests were done by implementing synthesized hydrogen reforming from ammonia, a second experiment included actual reformed hydrogen from ammonia, as shown in Figure 6.

A catalyst bed disc made of microfibrous porous media with platinum on alumina catalyst (Cellulose, 4 & 8 µm Ni fibers and 150-250 micron alumina powder, chemically impregnated with 8% chloroplatinic acid used for a loading of 10.8 wt % Pt), was used to burn hydrogen decomposed from ammonia.

It was noticed that there was significant difference between tests with cold apparatus and hot apparatus. The results from different tests are summarized on Table IV. After several tryouts, favorable conditions for flame stability of combustion of hydrogen reformed from ammonia through a catalyzer-impregnate microfibrous porous media were obtained.

Feasibility of ignition and combustion of ammonia depends on temperature of apparatus, the hotter the burner, the better ignition and combustion, thus facilitating the hydrogen reformation.

The microfibrous media can be easily shaped to conform to the head of a Free Piston Stirling Engine for Energy conversion purposes.
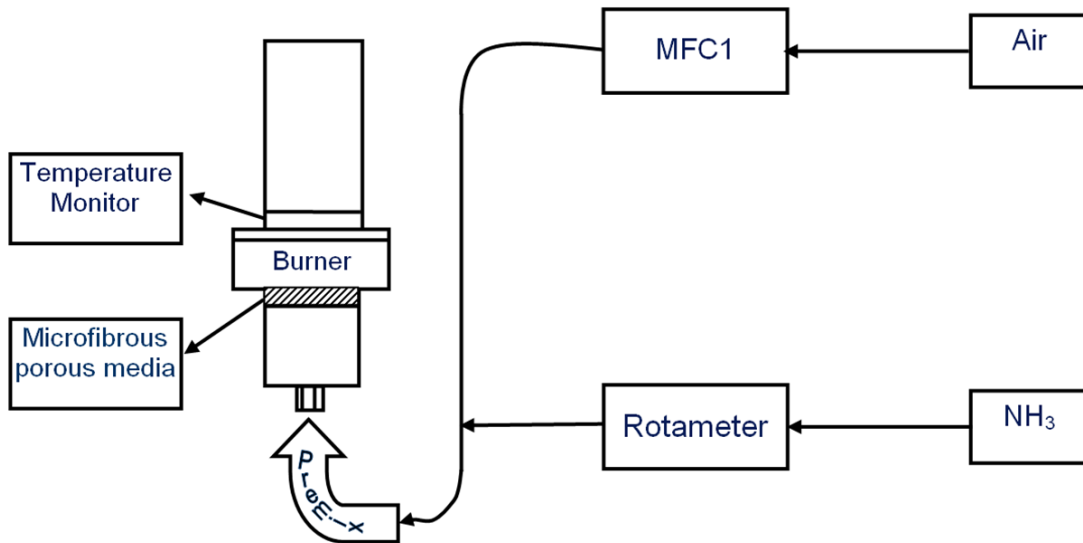

Figure 6. Schematics of System for hydrogen reformation from ammonia, using catalyst media.

Table IV. Summary of ammonia burner tests

Test No.	Conditions	Observations
1	Cold apparatus, NH$_3$ and Air.	Dfficult to ignite. NH3 combustion short-lived.
2	Hot apparatus, NH$_3$ and Air.	NH3 combustion ignites. Extinguished when air flow is stopped. Temperature: 740 °C
3	Synthesized reformate of NH$_3$, air and H$_2$, Ni media	Stable flame. Temperature: 990°C
4	NH$_3$ plus air thru catalyzed bed with 4.5 µm media.	Stable combustion. Temperature: 940°C.
5	NH$_3$ plus air thru catalyzed bed, 4.5 µm Ni media to prevent flame front going into media.	Stable burning. Temperature: 940 °C.
6	NH$_3$ plus air thru catalyzed bed, 4.5 µm Ni media to prevent flame front going into media.	Stable burning. Temperature: 940 °C.

IV. Hydrogen Powered FPSE

Hydrogen reformation from ammonia was demonstrated, so the next step was to investigate the possibility to run a FPSE with H$_2$. Because hydrogen is an odorless, colorless highly flammable gas, with a wide flammability range 4%-74% in air, and the amount of hydrogen necessary to produce oxygen-deficient atmospheres is within the flammable range, extreme care should be taken when handling it to avoid hazards associated with hydrogen and air mixture. It is not safe to premix hydrogen and air, so the mixture should be carried out at the combustion chamber.

A. H$_2$ Burner

A simple and safe hydrogen burner was designed, constructed and tested. It was coupled first to a dummy head acceptor for preliminary tests, and then to a real head acceptor of a 35We FPSE. The idea to have a dummy head acceptor was to have a similar heat transfer dynamics comparable to the real one at the FPSE head acceptor The gas flow and thus the temperature were manually controlled. Several tests on temperature and fuel flow rate were done.

The H$_2$ burner design was based on a previous device used for propane. The propane burner could be adapted to burn hydrogen by sealing off the air openings. However the size of the orifices at the burning port was too big for being used with hydrogen. A simple test hydrogen burner and direct fuel delivery apparatus was built instead.

The burner has smaller diameter ports for gas supply with no premixing with air and was made from a 0.25" diameter 304 stainless steel pipe piece bent into a circular shape to match the burning area of the 35We FPSE Head acceptor. The critical parameter in this new burner is the size of the orifices in the port. Because the velocity of a hydrogen flame is higher than that of propane, the flame tends to move backwards against the hydrogen flow. In order to prevent that the flame travels far beyond the burner body, the size of the orifices should be of such a diameter that the flame be extinguish. The minimum ignition energy becomes asymptotic to a very small spacing below which no ignition is possible. This distance is the quenching distance or quenching diameter.

Along with the quenching diameter used in the gas ports, other safety precautions should be taken specially when burning hydrogen. Between the safety measures taken before firing up the burner are the use of pressure regulator relief valve, flashback arrestors, and as a final inspection before fire up the burner, gas leaks were checked all along the gas lines.

The burner was installed following the safety measures listed above. The burner contains a gas valve which controls the fuel delivery, located just before the flow meter.

The valves were opened and the burner was fired up. A flame was visible, most likely because impurities coming from the metal surfaces, or from the inside of the pipe. After some minutes of running the visible flame had gone.

B. Temperature tests

A thermocouple was installed at the burner setup to register temperatures changes at the head acceptor. A digital output of the temperature was registered. A flow meter was instrumented to monitor the gas flow.

A preliminary test registered maximum temperature of 630 ºC which could be acceptable to run the FPSE. The gas flow was manually adjusted for a maximum temperature value which in turn could give a near stoichiometric combustion at the given conditions of air volume. A gas flow of 2.65 LPM indicated at the flow meter gave the higher temperature.

A second test for burning hydrogen during 35 minutes with a maximum fuel flow of 2.65 LPM resulted in temperatures of Table V. As expected, the temperature of the incoming gas was increasing, and also the pressure did so at a lower rate. From minute 25 to the end of the test the temperature was stabilized at around 749 ºC. During these tests the air-fuel mixture was set manually to get the higher possible temperature at the given flow of hydrogen and surrounding air volume.

Available temperature data from a propane burner coupled to a head acceptor of an air-cooled 80We FPSE[7] can be used to compare the temperature data obtained here and those reported for the real head acceptor, Figure 7.

Table V. Hydrogen Burner Test Data

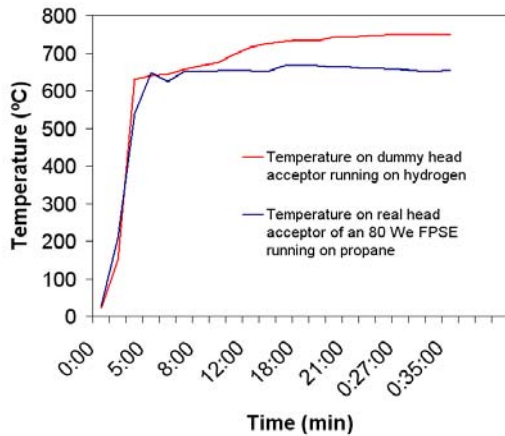| Time	Temperature on dummy head acceptor	Temperature of incoming H_2 at flow meter
0:00	22.4	26.15
0:25	150	26.23
1:00	245	26.46
2:00	302	26.50
3:00	423	26.52
3:15	630	26.53
5:00	640	26.53
6:00	643	26.54
7:00	657	26.54
8:00	667	26.6
9:00	674	26.58
10:00	698	26.73
12:00	717	26.72
14:00	725	26.75
16:00	731	26.98
18:00	735	27.0
19:00	734	27.05
20:00	742	27.62
21:00	742	27.72
23:00	746	27.95
25:00	748	28.22
27:00	748	28.28
30:00	749	28.51
33:00	750	28.77
35:00	749	28.95

Figure 7. Comparison of temperatures at dummy head acceptor with fuel-air set manually and a real head acceptor with controlled air-fuel mixture.

In a propane burner for FPSE the gas flow is set around 300 sccpm. The fact that the hydrogen flow rate can be increased much more than that for propane can be explained with the energy density of both fuels. This implies that it is necessary to increase considerably the flow rate for hydrogen in comparison to propane in order to achieve similar heat capacity.

The temperature of combustion can be assumed below the threshold level of about 1315°C (2400°F), and because of that, no significant amount of oxygen and nitrogen from the air may react to form nitrogen oxide (NOx) pollutant emissions.

C. Determination of the best Hydrogen Flow rate

In order to reach the maximum combustion temperature, the air-fuel mixture at the combustion chamber must be at least close to the stoichiometric value. Because in this case we have no way to measure the amount of air being used for combustion, and the only way to speculate about the stoichiometric value was the temperature measurement at the surface of the head acceptor. Another test was done by taking a value of reference, after temperature stabilization and changing the flow rate, first decreasing it and then increasing it. It was observed, Figure 8, that increasing the hydrogen flow rate, the temperature increased, then it reached a maximum and thus decreased again. It could be determined the best flow rate of 2.75 LPM according to the maximum temperature of 707ºC.
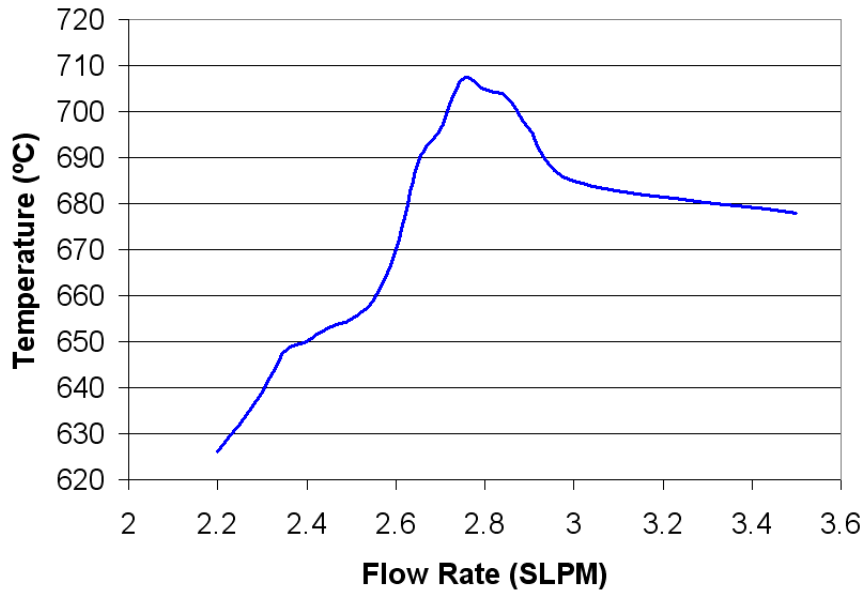
Figure 8. Determination of maximum hydrogen flow rate for the available amount of air.

D. Test of burner coupled to 35We FPSE.

This part of the project was undertaken to determine the feasibility of using an H_2 burner to supply thermal energy to a 35We FPSE, and to evaluate the potential for applying this system to a more efficient burner design.

In order to carry out a preliminary test on the 35We FPSE, the burner body was insulated with ceramic fiber, as shown in Figure 9. From past experiences with an electrical heater, it is known that the engine starts up when the temperature reaches 350ºC. In this case, for the hydrogen burner, during the preliminary test a temperature of 350ºC at the head acceptor's surface was not enough to crank up the engine; it was until it reached 412ºC that the engine started running. Thus it was evidenced that the temperature of the thermocouple is not the same as the temperature of the head acceptor. The engine was running for approx. 22 minutes and the temperature of the head acceptor was controlled by increasing or decreasing the flow of Air/H_2.

Figure 9. H$_2$ Burner coupled to a 35We FPSE

E. Monitoring of acceptor head temperature.

The initial way to monitor the temperature at the head acceptor of the 35We FPSE was attaching a thermocouple on the outer conical surface of the head acceptor. This way worked fine for the electrical heater in which the heat acceptor is heated from the inside of the cone by conduction. However, when burning gases, most of the heat transfer is due to convection at the external surface of the head acceptor, the temperature being measured is the flame temperature, which could be considerably higher than the temperature of the head acceptor. The convective heat transferred to the inside of the engine is slower. This is true especially when the burning process has just initiated. Based on this, the temperature at the inside of the cone of the head acceptor was measured at various stages of the burning process. I repeated the tests with another thermocouple with measurements at the inside of the conical head. I observed differences between the external surface and the interior up to 435ºC at the beginning of the burning process; obviously the head acceptor was not at that temperature. Still after some minutes of heating, temperature differences oscillating around 200ºC were registered, Figure 10. So, It was assumed that when the flame temperature indicates 650ºC, the head acceptor was somewhere around 500ºC or less. This assumption was corroborated, based in the fact that the engine normally starts running when the head acceptor is at around 350ºC (datum temperature), in this case the engine started to run when the external thermocouple registered 462ºC. Also

during the cooling down period, the engine stopped running when the temperature at the external surface reached 437ºC, almost 100º difference respect to the datum temperature.

The next calculations verify the heat capacity of the burner, it can be seen, at least in theory, that it could not heat the mass of the head acceptor in excess of 630ºC.
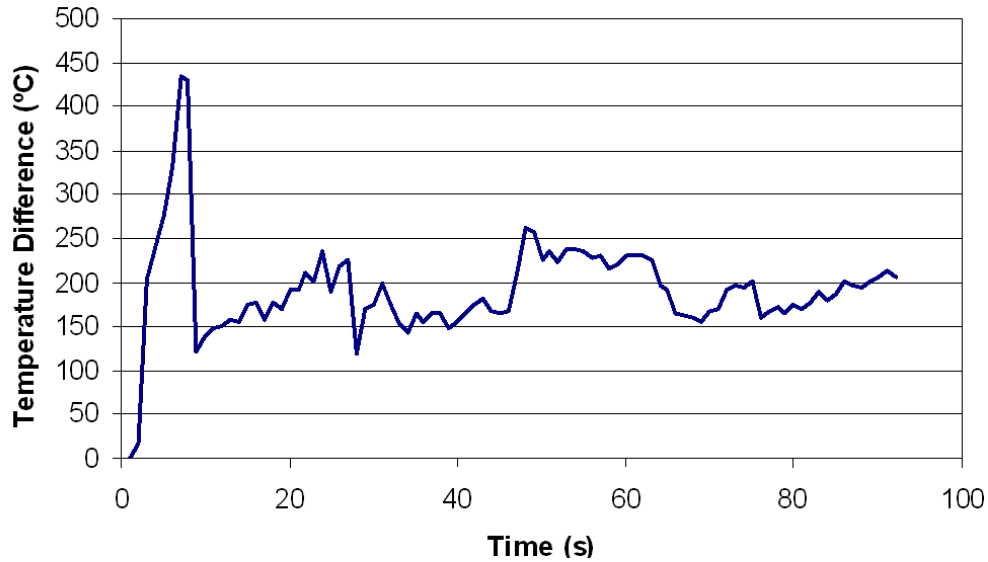

Figure 10. Temperature differences at heat acceptor's inner and outer surfaces.

F. Heat capacity of the H₂ burner

To calculate the heat capacity of the burner it is necessary to know the quantity of heat that hydrogen could provide to the burner. This would be a function of hydrogen's energy density and the amount of fuel being converted during combustion. Because the amount of hydrogen being completely burned is unknown, we rely on the flow rate measurement and the temperature of flame being obtained. As a rule of thumb, the highest burning temperature is obtained when a fuel is being oxidizing at its stoichiometric ratio. Thus it could be assumed that the flow rate for stoichiometric ratio was that which produced the highest temperature.

The contained energy density of hydrogen by volume at standard conditions of pressure and temperature (STP) is only 3.3 watt hours per liter as heat[8]. Assuming that the total amount of air currently present at the combustion chamber is being mixed with hydrogen, without any extra injected air, the best flow-rate for hydrogen under this condition was determined to be 2.75 slpm.

Then, the heat capacity of the burner (Q_b) in kW is:

$$Q_b = \varepsilon \times f \times \left(\frac{60}{1000} \right) \qquad (1)$$

here the energy density (ε) is given in Wh/l and the Flow rate (f) in LPM. Thus, for hydrogen at STP and the given flow rate is $Q_b = 0.544$kW (1857.8 BTU/hr). This is far below the energy level than a propane burner would provide at the same fuel flow rate. On the other hand it is enough to power up the 35We FPSE, which requires approximately 200W of heat.

V. Conclusion

To have sustained ammonia combustion during a long period, optimum flow rates and mixtures should be determined; otherwise it is difficult to maintain ammonia-hydrogen combustion. In order to find out those optimum values a burner was placed upside-down with the flame confined, in the cylindrical combustion chamber. Several mixtures ammonia-hydrogen were proven to combust in the burner, and temperatures were varied from 200ºC to approx 1100ºC, indicating that in some cases the combustion was incomplete, and in others an excess air was cooling the flame. Once the favorable conditions for flame stability were determined, the burner operated in right-side-up position, a catalyzed microfibrous media was used in the burner to reform hydrogen form ammonia obtaining temperatures from 670ºC to 1020ºC depending on the power densities considered from 200W up to 500W. It was not possible to have the burner operating in right-side-up position at lower energy densities, i.e. 100W, but

stable combustion was observed at the 200W power level in the right-side-up orientation with mixed air and ammonia. A simple and safe hydrogen burner was constructed and tested with injected air supply and heat recuperation. The gas flow, the air flow thus the temperature were manually controlled. Several tests on temperature and fuel-air flow rates were done. Based on the findings and feelings of burning hydrogen with this basic burner, a more sophisticated high efficiency burner can be designed. This part of the project was undertaken to determine the feasibility of using a hydrogen burner using hydrogen reformed from ammonia to supply thermal energy to a 35We FPSE, and to evaluate the potential for applying this system to a more efficient burner design.

VI. References

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