2016

Design and Investigation of Vitiated-Air Heater for Oblique Detonation-Wave Engine

Matthew M. Hoban
University of Central Florida

DESIGN AND INVESTIGATION OF VITIATED-AIR HEATER FOR OBLIQUE DETONATION-WAVE ENGINE

by

MATTHEW HOBAN

A thesis submitted in partial fulfillment of the requirements
for the Honors in the Major Program in Aerospace Engineering
in the College of Engineering and Computer Science
at the University of Central Florida
Orlando, Florida

Fall 2016

Thesis Chair: Dr. Kareem Ahmed

ABSTRACT

A facility was designed to provide high-enthalpy, hypersonic flow to a detonation chamber. Preliminary investigation identified 1300 K and Mach 5 as the total temperature and Mach number require to stabilize an oblique detonation wave inside the detonation chamber. Vitiated-air heating was the preheating method chosen to meet these capabilities. The vitiator facility heats compressed air while still retaining about 50% of the original oxygen content. Schlieren flow visualization and conventional photography was performed at the exit plane of a choke plate, which simulated the throat of a converging-diverging nozzle. A shock diamond formation was observed within the jet exhausting out of the choke hole. This is a clear indication that the facility is capable of producing hypersonic flow. A stoichiometric propane-air mixture was burned inside the combustion chamber. A thermocouple survey measured an average temperature of 1099 K at the exit plane of the mixing chamber; however, the actual temperature is likely higher than this, because cool, ambient air could be seen mixing with the hot, vitiated air near the exit plane. Because the adiabatic flame temperature of propane-air is lower than that of hydrogen-air, if hydrogen is used to vitiate the air, the facility is capable of meeting the 1300-K objective.

ACKNOWLEDGEMENTS

Jonathan, this thesis would not have been possible without your mentoring. You've been an academic role model for me to look up to this past semester. Thank you for the hundreds of hours of help. Your one-of-a-kind intelligence and humor will take you far in life.

Jay and Wilmer, both of you were always there to lend a hand. You taught me more than just basic things like what a tapered thread is. You taught to offer help whenever possible without expecting anything in return.

Dr. Ahmed, I will always be grateful for the research opportunity you've given me. You always pushed me to settle for nothing short of excellence. This thesis would not have been possible without your advice and support.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER ONE: INTRODUCTION

An engine which combusts a fuel-air mixture using an oblique-detonation wave is desired as a means to increase thermal efficiency. The detonation causes a large pressure spike and rapid material conversion that makes it resemble an isochoric thermodynamic cycle. Because detonation waves propagate hypersonically, stabilizing the wave inside a combustion chamber creates many challenges including preheating, fuel-air mixing, combustor inlet flow uniformity, and ground testing, of which this thesis focuses on the first. If room temperature, compressed air is expanded to hypersonic speeds to feed the detonation with oxygen, the air must be sufficiently preheated to account for the large drop in static temperature. If the air is not preheated, then the static temperature drop may cause icing in the detonation chamber and prevent ignition. If preheated air is accelerated by a nozzle, the main fuel must be injected at some point in the flow where autoignition will not occur before the detonation wave. Ideally, the flow entering the detonation chamber should be well mixed with fuel and uniform in temperature, pressure, and velocity. Simulating hypersonic flight conditions in a ground-testing facility is itself a challenge and requires analysis and correction before extrapolation to normal flight conditions. This section discusses detonation wave fundamentals, a review of detonation research, and several topics involved in obtaining the hypersonic flow condition.

Combustion Modes

Detonation and deflagration are two different modes of combustion. Turns [1] explains fundamental differences between both and reviews methods for estimating detonation velocities. Suppose a combustible mixture passes through a standing shock wave causing its temperature and pressure to spike. If this spike brings the mixture to within its ignition limits, the process of combustion initiates. If the mixture ignites downstream of the shock wave such that the ignition does not affect the shock wave, the combustion process is classified as shock-induced. If the ignition couples with and sustains the shock wave, the process is classified as a detonation.

Detonation waves are therefore related to shock waves in that the energy released by combusting the fuel-oxidizer mixture sustains the shock wave. Several changes in the upstream and downstream properties of a detonation and a shock wave are similar because of this relationship.

Friedman [2] summaries the qualitative differences between upstream and downstream properties of the two combustion modes. His summary is replicated in Table 1, in which M is Mach number, v is velocity, P is pressure, T is temperature, and ρ is density. The subscripts u and b refer to the unburned and burned states of a combustible mixture. The large compression and temperature ratios of the detonation wave make it a desired mode of combustion. Both combustion modes are similar in that temperature increases as energy is released.

A key difference between a normal detonation and a normal shock is that flow downstream of a normal shock is subsonic, whereas flow downstream of a normal detonation is locally sonic. Propagation speeds for deflagrations are subsonic, whereas those for detonations are hypersonic.

Table 1: Differences Between Detonation and Deflagration in Gases (from Ref. 2)

	Usual Magnitude of Ratio	
Ratio	Detonation	Deflagration
M_u	5-10	0.0001-0.03
v_b/v_u	0.4-0.7	4-16
p_b/p_u	13-55	0.098-1.000
T_b/T_u	8-21	4-16
ρ_b/ρ_u	1.4-2.6	0.06-0.25

This allows for rapid material conversion which contributes to the high efficiency of the detonation mode of combustion. Unlike a deflagration in which gas expansion causes the flow speed and Mach number to increase across the wave, these parameters decrease across a detonation wave. Lastly, a deflagration is essentially isobaric, whereas pressure rises sharply across a detonation.

Detonation Research

Chapman [3] was the first to approximate the detonation velocity of a combustible mixture. Among other assumptions, his approach was one-dimensional and relied on constant, equal specific heats across the detonation wave. Kuo [4] developed a more exact formula to the detonation velocity. Gordon and McBride [5] approached the solution numerically by writing a computer program that calculates detonation parameters. In this program, initial estimates of the detonation pressure and temperature are improved by a recursion formula and then iteratively corrected using the Newton-Raphson procedure. This numerical method was critical in the design and investigation of the vitiated-air heater.

Kailasanath [6] reviewed detonation research and explained why detonation waves are attractive for propulsion applications. The rapid release of energy caused by the detonation wave leads to more compact and efficient engines. The high propagation speeds of the detonation wave prevent pressure equilibration. Instead, the thermodynamic cycle of a detonation wave resembles that of an isochoric process which is almost twice as efficient as the isobaric process seen in conventional propulsion systems. Stabilizing a detonation wave in a propulsion system, however, is challenging.

Normal Detonation Wave

Nicholls and Dabora [7] studied standing normal detonation waves. The schematic of their experiment is replicated in Figure 1. By operating the nozzle at underexpanded conditions, a Mach disk, or rather a shock wave that is nearly normal to the flow, forms after the zone of silence behind the throat. This shock wave spikes the temperature and pressure and brings the combustible mixture to within its ignition limits. If the energy released in the combustion zone couples with and sustains the shock wave, the detonation wave will form. They assessed the strength of the detonation wave using chemical and aerodynamic criteria. The first of which is based on temperature, which is related to the ignition delay time and explosion limit, and the second of which is based on observation of the shock structure. Nicholls and Debora concluded that in some cases, strong detonation waves were formed, but only a portion of the combustion zone coupled with the shock wave.

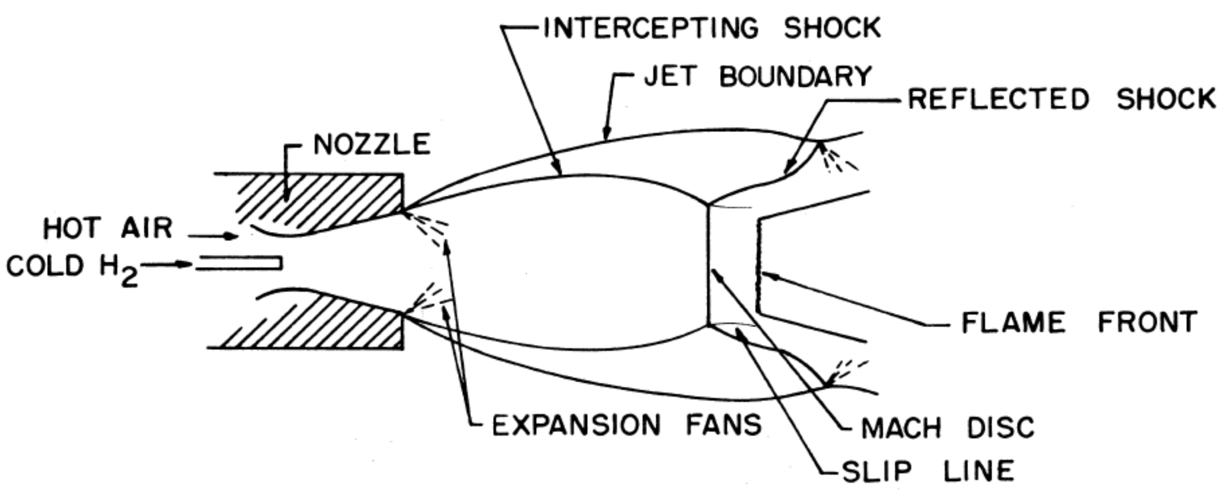


Figure 1 Schematic of Normal Detonation Wave Standing at Nozzle Exit (from Ref. 7)

Oblique Detonation Wave

Menees et al. [8] analyzed a conceptual vehicle that used an oblique detonation-wave engine. If a combustible mixture flows faster than its C-J Mach number, then an oblique detonation wave can form. This is attractive for hypersonic vehicles because as the flow passes through the oblique denotation wave, its tangential component will remain supersonic while its normal component will become subsonic or sonic. Figure 2 shows a schematic of an oblique detonation wave attached to an inclined surface. Menees et al. identified that the main advantage of an oblique detonation-wave engine over a conventional scramjet engine is that the rapid material conversion allows for a shorter and more compact engine.

Figure 2 Schematic of Oblique Detonation Wave (from Ref. 8)

It is important to note that Kailasanath [6], in his review of the application of detonation waves to propulsion systems, did not find any studies in which an oblique detonation-wave engine was successfully built and tested. Recent studies have only realized that in most situations, a detonation wave will not form from shock-induced combustion.

Hypersonic Conditions

Preheating Method

Because detonation waves propagate hypersonically and consequently need a hypersonic combustible mixture to feed the detonation, the ratio of static to stagnation temperature is a critical concern in ground testing. Through manipulation of conservation equations, the ratio of static to total temperature can be written as,

$$\frac{T}{T_t} = (1 + \frac{\gamma - 1}{2} M^2)^{-1}$$

for a perfect gas with constant specific heats. In this equation, T is the static temperature, T_t is the total temperature, γ is the specific heat ratio, and M is the Mach number of the gas.

As the Mach number of a flow enters the hypersonic regime, the static temperature drops dramatically. For example, as non-moving air at 300 K is accelerated to Mach 5, the static temperature will drop to 50 K. This becomes an obstacle in achieving detonation in a ground test, because the mixture will be too cold to ignite. Thus, the mixture must be preheated to hotter temperatures in order to achieve detonation in the combustion chamber.

Preheating air can be achieved via several methods including passing cold air through hot ceramic beds, electric resistance heating, arc heating, shock heating, and in-stream combustors [9]. The latter method is attractive because of its relatively low cost, low risk, and wide-operating range. In this method, a conventional combustor is placed upstream of the nozzle. The combustor produces hot gases that mix with cold air, resulting in the high total temperatures necessary for hypersonic combustion. A disadvantage of this ground-testing method, however, is that the chemical composition of the air entering the detonation chamber does not match the composition of the air that the it would intake during normal flight. Air that is heated using an in-stream combustor is referred to as “vitiated air” because of its reduced oxygen content and altered chemical composition [1], and this in-stream combustor is referred to as a vitiated-air heater or “vitiator” for short. Another disadvantage is that stabilizing a flame inside the vitiator can be challenging because of its location upstream of a choked, high-area-ratio nozzle.

Vitiation Effects

Vitiation effects result from heating the air flow via an in-stream combustor. This term broadly refers to the thermodynamic, chemical, and kinetic effects that result from using vitiated air for combustion. Different fuels used in the vitiator will result in different vitiation effects; therefore, fuel selection and vitiation effects are an important consideration in designing a vitiator. Several vitiation effects have been identified.

Edelman and Spadaccini [10] conducted a theoretical investigation of vitiation effects in scramjet engines and made several key conclusions. At hypersonic conditions, water vapor from hydrogen vitiation may condense, and a high total pressure will increase the rate of this condensation. Among other consequences, this will reduce the allowable inlet Mach number. Recombination of free radicals upstream of the ignition zone will alter thermodynamic and chemical-kinetic effects on flame stabilization, rate of combustion, ignition, and energy release. The reduced molar mass of the hydrogen-vitiated air will lower the mass capture at the scramjet inlet. Loss of thrust will result from the thermodynamic heat capacity and dissociation effects. For scramjets using hydrogen-vitiated air at total pressure 2000 psi, fuel mass fraction 0.023, and Mach 9.5; thrust was about 10% lower than scramjets using equivalent clean air. The free radicals and other active species will decrease the ignition delay time, and, depending on the initial conditions, the water vapor will further affect this delay time.

Flame Stabilization

Huellmantel et al. [11] proposed an alternative technique to stabilizing a flame by creating a recirculation zone within a cavity. This study sought to reduce the drag penalty associated with conventional bluff bodies. Several cavity shapes were investigated and compared a conventional

90° V-gutter. Some of the shapes that were tested resulted in a wider stability limit and a decreased drag penalty.

A notable shape proposed by the study is characterized by a rearward-facing step, followed by a flat recess length and an inclined plane. Flames in cavities with a step height and recess length that fully captured the recirculation zone were found to be more stable. The slope of the inclined plane did not have an appreciable effect on flame stability but rather was intended to mitigate drag. Deeper cavities were found to have wider stability limits.

Gabruk and Roe [12] measured mean and turbulent velocities for reacting and non-reacting flows in a combustor using an axisymmetric, rearward-facing step. The recirculation regions of the two types of flows were significantly different. The reattachment length for reacting flow was found to be 52% shorter than the non-reacting flow despite the increase in flow speed from heat release. The measured reattachment length for the reacting flow was 3.5 times the step height, whereas for non-reacting flow, this measurement was 6.75 step heights. The reacting flow was also found to have greater max negative velocities. These characteristics combine to make the recirculation region stronger and more compact.

Scope of Study

An ODWE has yet to be built and tested [6], so the investigation of the vitiator designed for an ODWE is an area of research that demands attention. This study outlines the design and investigation of a facility capable of producing the high-enthalpy, hypersonic flow conditions necessary to form and stabilize an oblique detonation wave.

CHAPTER TWO: FACILITY DESIGN

Test Section

The schematic of the test section is shown in Figure 3. The full facility consists of five separate pieces: the combustor, two mixing chambers (only one shown), a perforated plate (not shown), and a choke plate. The facility is capable of providing a converging-diverging nozzle with high-enthalpy, vitiated air.

Flanges with sixteen bolt holes connect the pieces to each other. In addition to sealing the interfaces between the flanges with red silicon, these sixteen large bolts press the flanges together to prevent leakages.

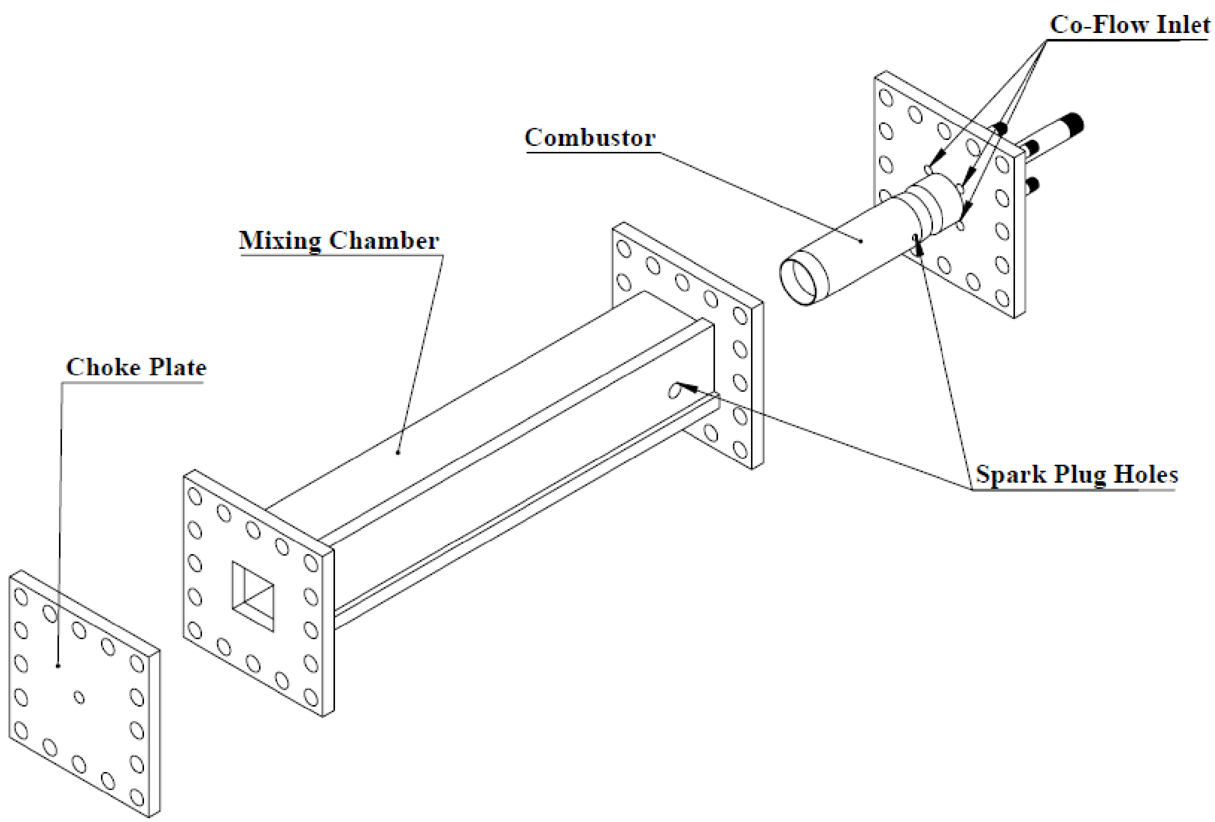


Figure 3 Schematic of Test Section

Two holes are labeled in Figure 3 for a spark plug. When the combustor piece and first mixing chamber are bolted together, these two holes line up concentrically. A conventional NGK automotive spark plug (model number: 6386 LFR5A-11) threads into the outer hole and its tip protrudes into the inner hole. A Beckett electronic igniter (model number: 51771U) is used to activate the spark plug and ignite the fuel-air mixture.

Attached to the combustor piece are four 1/8 NPT pipes (shown in Figure 3) that coaxially inject room-temperature air along the outside of the combustion chamber. This referred to as co-flow air. The combustor was designed so that the co-flow passes around the combustion chamber in order to extract heat from the chamber walls. The co-flow then mixes with the hot gas from the combustion chamber in order to achieve the high temperature necessary for the detonation wave. The ratio of hot gas to co-flow is roughly 1:1, but can be actively controlled using valves.

Combustion Chamber

Three axisymmetric combustion chambers were tested, two of which had a step flameholder and the other, a half-v gutter. The step combustor is shown in Figure 4. A premixed fuel-air mixture is supplied to the combustion chamber. As the flow reaches the inlet to the combustion chamber, it separates at the step and then reattaches on the chamber wall at some point

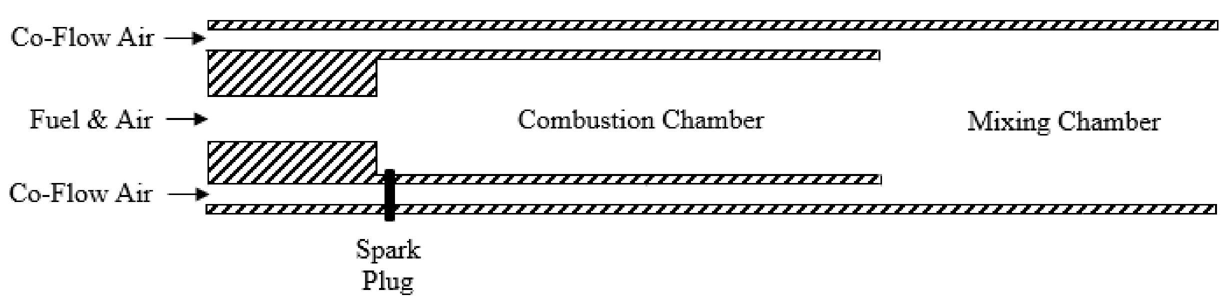


Figure 4 Cutout View of Test Section

downstream. In between the point of separation and reattachment is a recirculation zone in which the local velocity is low enough to sustain the flame.

The size of the step was constrained by the maximum diameter of the combustion chamber that could fit inside the 45 x 45 mm mixing chamber, while still providing enough clearance for the co-flow to pass by the combustion chamber. The combustion chamber is a modified 1¼ NPT, schedule 40 pipe. The threads were grinded off to smoothen the finish, and a hole was drilled immediately after the step for the spark plug tip. The step itself was fabricated from a 50-mm long rod by drilling the inlet hole and turning down part of it for the combustion chamber to slide onto. The inner dimensions of the inlet and combustion chamber are 13 and 35 mm, respectively, which correspond to a step height of 11 mm. The chamber length was 125 mm, which is more than sufficient to account for a shallow flame propagation angle.

Mixing Chamber

Both the hot gas from the combustion chamber and the cool co-flow air issue out into the mixing chamber. The entire mixing chamber consists of three pieces: two plenums and a thin perforated plate (holes with 6-mm diameter, 58% open area, and 20 gauge). The degree of mixing was determined experimentally. If the temperature profile at the exit plane of the first plenum was non-uniform, the second plenum could be added. If this extra length was still insufficient, the perforated plate could be sandwiched in between the mating flanges of both plenums.

Choke Plate

The design condition of Mach 5 flow at 1300-K total temperature were determined based on detonation parameters which were calculated using a numerical method developed by Gordon and McBride [5]. To achieve oblique detonation, the nozzle must expand the flow to Mach 5, so that Mach number of the flow is greater than its C-J Mach number [3]. The static temperature after expansion must be high enough to ignite a combustible mixture. The minimum temperature for this was considered to be 215 K. From isentropic relations, the total temperature will be six times higher (about 1300 K) which the facility is capable of providing.

The nozzle requires 0.165 kg/s of hot, vitiated air from a source pressure of at least 1.85 MPa. The choke plate shown in Figure 3 is used to simulate the choked throat of the nozzle. The area of the choke hole (10 mm diameter) is equivalent to that of a 9 x 9 mm nozzle throat. This throat was sized to be 25 times smaller than the 45 x 45 mm detonation chamber in order to provide the area ratio necessary for Mach 5 flow.

Fuel-Air Supply

A propane-air mixture at 0.34 MPa was used to assess the performance of the vitiator, although to mitigate vitiation effects from free radicals, a hydrogen-air mixture is expected to be used when testing the detonation chamber. Because the adiabatic flame temperature of a stoichiometric propane-air mixture is about 200 K lower than a hydrogen-air mixture, a temperature lower than 1300 K downstream of the mixing chamber is to be expected.

A common compressed air tank supplied the co-flow air and combustion chamber air. The main airline coming from tank was plumbed into a tee-joint pipe fitting to split the air. The facility was capable of controlling the split using valves, but for most of the tests, the valves were kept open and a 1:1 ratio was assumed. The air flow was not regulated, but the tank pressure was reset to the desired level before each trial.

After the main air split, propane was mixed into the combustor air supply using a tee joint. Although the propane was stored in compressed gas tanks, it was regulated down to match the pressure of the air flow. One meter of flexible hosing and piping connected the tee joint to the combustion chamber inlet channel. This also served as a channel to mix the fuel and the air.

After the main split, the co-flow supply plumbs into a manifold which splits the air into four 1/8 NPT pipes. As previously discussed, there are three purposes of the co-flow. (1) The co-flow extracts heat out of the combustion chamber walls. (2) The room-temperature co-flow mixes with the hot gas from the combustion chamber in order to produce the desired total temperature. (3) The co-flow air was separated from the combustion chamber air, so that approximately 50% of the original oxygen content will be left for the detonation chamber. The facility is, however, capable of pre-enriching the oxygen content of the air in order to provide the normal oxygen percentage to the detonation chamber.

CHAPTER THREE: EXPERIMENTAL METHODS

Schlieren Flow Visualization

Schlieren is an imaging technique which takes advantage of light deviation caused by an inhomogeneous transparent medium. When used on a gas jet, density gradients appear as localized light or dark regions. This imaging was done to assess the capability for the facility to provide hypersonic flow. The choke plate, previously discussed in Chapter 3, was added to the end of the mixing chamber. This choke plate had a small hole which had an area that was equivalent to the throat of a Mach 5 converging-diverging nozzle. When the facility was properly choked, a shock diamond could be seen exhausting out of the choke hole.

Flow Measurements

Compressed air and propane were used as the combustible mixture. The target volumetric air-fuel ratio inside the combustion chamber was 23.80. For atmospheric testing (no choke plate), the total air flow rate was set to 20 SCFM which was split between the co-flow and the combustion chamber. To burn at the stoichiometric air-fuel ratio, the propane was set to 0.42 SCFM, and the color of the flame was checked to ensure this ratio.

The source of the air was a large, compressed gas tank which was reset to provide 50 psi flow before each trial. A pressure regulator was not used on the air supply because of choking concerns, but the pressure was monitored using an Ashcroft pressure regulator (± 2.5 psi). The total air flow rate was controlled using Dwyer flow meter (model number: RMC-122-SSV, ± 0.25 SCFM).

The propane supply was regulated down to provide 50 psi flow using a Husky pressure regulator (Model number: HDA70703AV, ± 2.5 psi). The flow rates were controlled using an

Alborg flow meter (model nom. 044-40CA, ± 0.04 SCFM). The air calibration curve provided by the manufacturer was modified using a conversion factor to measure propane.

Temperature Measurements

A Type-K thermocouple (± 2.2 K) was used with an Omega thermocouple reader (model number: 210460) to measure the temperature downstream of the mixing chamber. This thermocouple was chosen because its maximum temperature was safely above the predicted temperature. The thermocouple was inserted approximately 6 mm into the mixing chamber from its open-ended exit plane. Consequently, mixing of hot, vitiated air with ambient air could not be prevented without drilling a hole inside the mixing chamber, so it is important to note that the predicted readings are lower than the average of the co-flow and combustion chamber gases.

CHAPTER FOUR: RESULTS

Shock Diamond Formation

The vitiated-air heating facility ("vitiator") was designed to be capable of providing high-enthalpy, Mach 5 flow to a detonation chamber. A choke plate was added downstream of the mixing chamber to simulate the throat of a nozzle. This aluminum plate can be seen in the bottom of Figure 6. The area of the hole, out of which the gas jet is exhausting, is equivalent to a 9- x 9-mm Mach 5 nozzle throat. These throat dimensions were chosen to provide an area ratio of 25 to the 45- x 45-mm detonation chamber.

A shock diamond formation can be seen in the gas jet exhausting out of the throat in both images of Figure 6. This pattern consists of a series of Mach disks (nearly a normal shock wave)

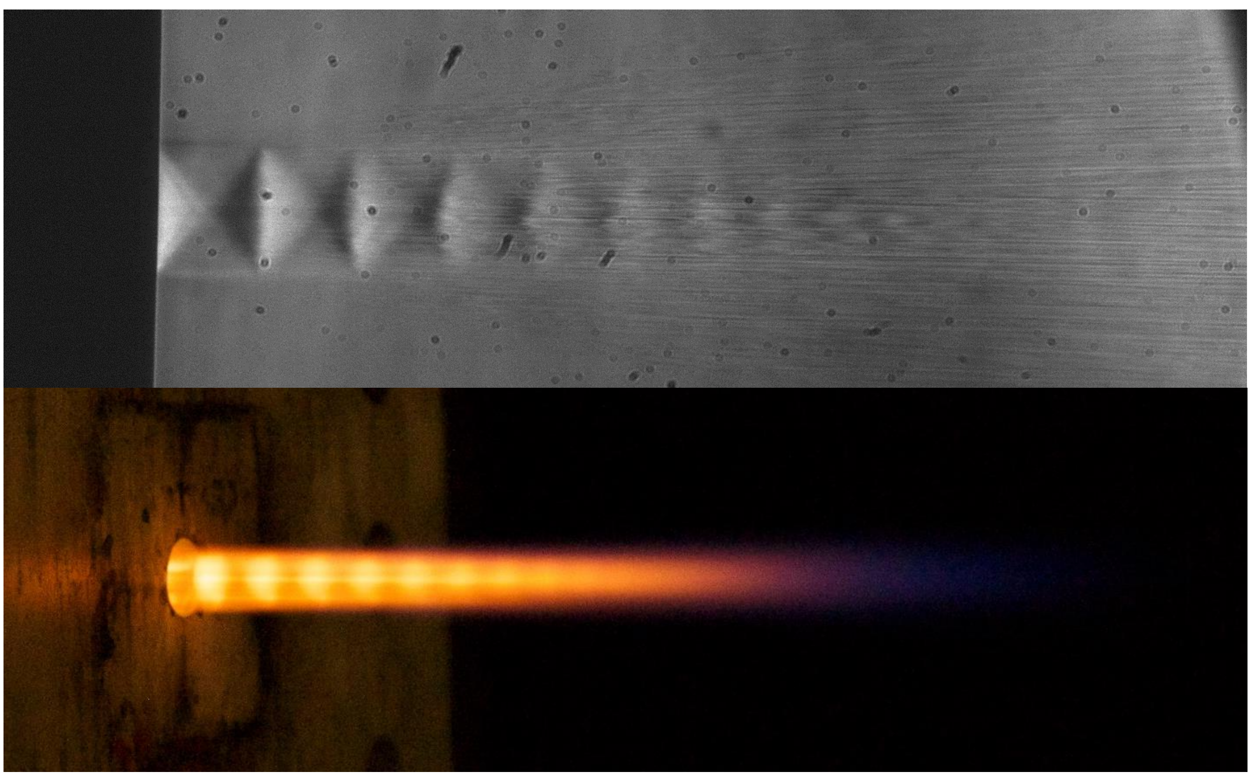


Figure 5 Schlieren Image of Non-Reacting Jet (top), Conventional Image of Reacting Jet (bottom)

formed by pairs of oblique shocks and Prandtl-Meyer expansion fans. This formation is a readily apparent confirmation that the facility is properly choked and capable of hypersonic flow.

A combustion instability was observed when the facility was back-pressured with the choke plate. This instability caused the flame to flutter rapidly while making a frequent sputtering sound. The luminous, red flame that is seen in the reacting image of Figure 6 was an unintended feature of the vitiator facility, because such a flame is an indication of inefficient, rich combustion.

The strength of the instability was determined to correlate with the air-fuel ratio. Increasing the fuel flow rate past stoichiometric levels reduced the strength of the instability. Any attempt to lean the rich mixture to the stoichiometric ratio would cause blowout.

Atmospheric Testing

The choke plate was removed to photograph the step-stabilized flame under atmospheric condition (not back-pressured). Figure 7 shows two versions of the same image. The image on the right was altered to highlight the axial uniformity of the flame. A small, brighter region can be seen in the upper-left section of the combustion chamber. This was the result of a minor, correctable fabrication flaw: the inlet hole was approximately 2 mm off the center of the combustion chamber. This caused a slight non-uniformity in the recirculation region.

Because the luminosity of the flame is directly caused by the air-fuel ratio, the flame's color was very important in verifying the propane-air ratio. At $\varphi = 1$, this mixture burns at a specific shade of blue which can be observed from a safe distance by a trained eye.

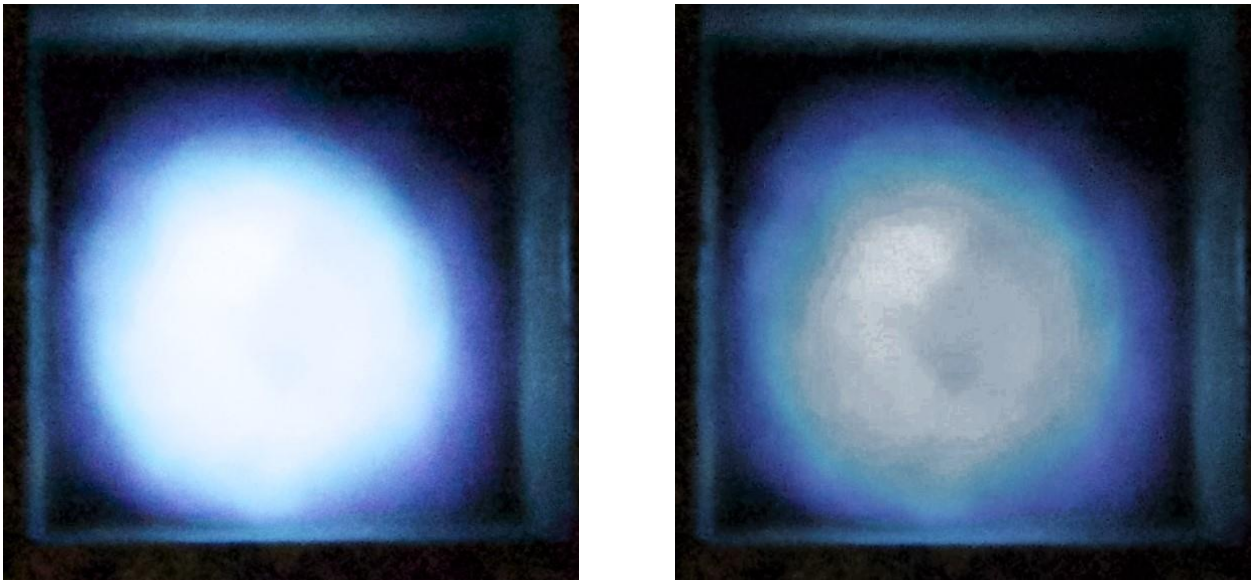


Figure 6 Flame under Atmospheric Condition: Unaltered Image (left), Altered Image (right)

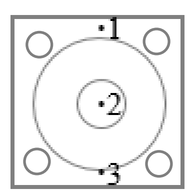
Temperature Profile

A thermocouple survey was performed at several positions along the exit plane of the mixing chamber to assess whether the co-flow had uniformly mixed with the hot gas from the combustion chamber. Data from three of those positions are given in Table 2. The condition that produced these results was stoichiometric, atmospheric combustion, which produced a total vitiated-air flow rate of 9.67 L/s.

If the mixing chamber of the facility was configured without the perforated plate and second plenum, the temperature profile was found to be non-uniform. After many trials, heat caused the thin-walled, 125-mm-long combustion chamber to warp downward. The hot gas consequently issued out of the chamber at an angle of approximately 10° below horizontal. As a

Table 2: Temperature Profile

Position	Temperature {K}	95% Conf. Interval
1	936	±9
2	1161	±9
3	1199	±10



result, the temperature varied along the vertical axis such that colder flow exhausted out of the upper portion of the mixing chamber. The non-uniformity was mitigated by adding the second plenum, although this second plenum absorbs heat from the hot, vitiated air. To prevent this non-uniformity, the outer diameter of the combustion chamber will be 45 mm in a future revision of the design, so that the chamber rests on the bottom wall of the plenum.

If the combustion chamber issued hot gas horizontally, it is reasonable to assume the exit plane of the first plenum would be properly mixed. The average of the data in Table 2 can be used to conservatively predict that the resulting temperature would then be about 1099 K. Because the adiabatic flame temperature of propane and air is lower than that of hydrogen and air, the results in Table 1 confirm that the facility is capable of the 1300 K design objective if hydrogen were used instead to vitiate the air.

CONCLUSION

A facility was designed to provide high-enthalpy, hypersonic flow to a detonation chamber. Preliminary investigation identified 1300 K and Mach 5 as the total temperature and Mach number of the combustible mixture that the detonation chamber will need to stabilize an oblique detonation wave. Vitiated-air heating was the preheating method chosen to meet these capabilities. This "vitiator" heats compressed air while retaining 50% of the original oxygen content before the air is expanded to Mach 5 in a converging-diverging nozzle. Air from a common compressed air source is split into two so that half of the air is routed into the combustion chamber and the other half flows coaxially ("co-flow") along the outside of the combustion chamber. The relatively cold co-flow air then mixes with the hot combustion products in a mixing chamber.

Schlieren flow visualization and conventional photography was performed at the exit plane of a choke plate, which simulated the throat of a converging-diverging nozzle. A shock diamond formation could be seen within the jet exhausting out of the choke hole. This is a clear indication that the choke point of the facility is at the proper location, and the facility is capable of producing hypersonic flow.

A thermocouple survey assessed the temperature profile at the exit plane of the mixing chamber. A region of relatively cold air was measured in the upper portion of the mixing chamber. After inspecting the facility, the high-temperature testing was found to have caused the thin-walled, 125-mm long combustion chamber to warp downward. In a future design revision, the outer diameter of the combustion chamber will match the 45- x 45-mm inner dimensions of the plenum, so that the bottom of the combustion chamber will rest on the bottom surface of the plenum. The hot gas will then issue horizontally into the mixing chamber and will mix sufficiently with the co-flow as intended.

The thermocouple survey measured an average temperature of 1099 K at the exit plane of the mixing chamber; however, the actual vitiated air temperature is likely higher than this, because cool, ambient air could be seen mixing with the hot, vitiated air near the exit plane. Nevertheless, because the adiabatic flame temperature of propane-air is lower than that of hydrogen-air, if hydrogen is used instead to vitiate the air, the facility is capable of the 1300-K design objective.

REFERENCES

[1] Turns, S. R. (2000). *An Introduction to Combustion: Concepts and Applications* (3rd ed.). Boston: WCB/McGraw-Hill.

[2] Friedman, R. “Kinetics of the Combustion Wave”, *Journal of the American Rocket Society*, Vol. 23, No. 6 (1953), pp. 349-354.

[3] Chapman, D. L., “On the Rate of Explosion of Gases,” *Philosophical Magazine*, 47: 90 103 (1899).

[4] Kuo, K. K. (1986). *Principles of Combustion* (2nd ed.). New York: Wiley.

[5] Gordon, S., and McBride, B. J., “Computer Program for Calculation of Complex Chemical Equilibrium Compositions, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations,” NASA SP-273, 1976.

[6] Kailasanath, K., "Review of Propulsion Applications of Detonation Waves", AIAA Journal, Vol. 38, No. 9 (2000), pp. 1698-1708.

[7] Nicholls, J. A., and Dabora, E. K., “Recent Results on Standing Detonation Waves,” *Eighth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 1962, pp. 644–655.

[8] G. P. Menees, H. G. Adelman, J. L. Chambier, and J. V. Bowles. "Wave Combustors for Trans-Atmospheric Vehicles", Journal of Propulsion and Power, Vol. 8, No. 3 (1992), pp. 709-713.

[9] Muylaert, J., *Technologies for Propelled Hypersonic Flight: Introduction*. Vol. 2, Subgroup 2: Scram Propulsion. Neuilly-sur-Seine Cedex, France: North Atlantic Treaty Organization, Research and Technology Organization, 2006.

[10] Edelman, R. B., and Spadaccini, L. J., “Theoretical Effects of Vitiated Air Contamination on Ground Testing of Hypersonic Airbreathing Engines,” *Journal of Spacecraft and Rockets*, 6, No. 12, Dec., 1969, pp. 1442-1447.

[11] L. W. Huellmantel, R. W. Ziemer, A. B. Cambel. "Stabilization of Premixed Propane Air Flames in Recessed Ducts," *Journal of Jet Propulsion*, Vol. 27, No. 1 (1957), pp. 31-34.

[12] Gabruk, R. S., and Roe, L. A., “Velocity Characteristics of Reacting and Nonreacting Flows in a Dump Combustor.” *Journal of Propulsion and Power*, Vol. 10, No. 2, (1994), pp. 148-154.