RECEIVED
OCT 12 2016
By

Entered

Honors Thesis Proposal

For

Design and Investigation of Vitiated-Air Heater for Scramjet Engine

Matthew Hoban

Kareem A. Ahmed, Ph.D.
Thesis Committee Chair
Department of Mechanical and Aerospace Engineering

Charles H. Reilly, Ph.D.
HIM Coordinator
College of Engineering and Computer Science

Jeffrey L. Kauffman, Ph.D.
Committee Member from Major
Department of Mechanical and Aerospace Engineering

Jayanta S. Kapat, Ph.D.
Committee Member from Outside Major
Department of Mechanical and Aerospace Engineering

Introduction and Motivation

Research on supersonic combusting ramjet (scramjet) engines is being conducted throughout the world to access their viability in certain military applications and space-delivery systems. There are three notable differences between conventional jet engines and scramjet engines. (1) Conventional jet engines use turbomachinery to compress air to high pressures, whereas scramjet engines compress air by ramming fast-moving air into an inlet body. (2) Conventional jet engines travel through air at subsonic or low-supersonic speeds, whereas scramjets travel at hypersonic speeds. (3) Air flows inside conventional jet engines at subsonic speeds, whereas air flows inside scramjet engines at supersonic speeds. Today, scramjet research focuses on four critical categories: fuel-air mixing, engine scaling, supersonic combustion, and ground testing [1]. The proposed research falls into the latter two categories.

The Air Force Office of Scientific Research is currently directing investigations on supersonic combustion via a detonation wave. To achieve combustion in this mode, a mixture of fuel and air, which is below its ignition temperature, flows into a standing shock wave in the combustion chamber. This wave spikes the temperature and pressure of the mixture to within its ignition limits. 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 [2].

To simulate the inlet conditions of hypersonic flight using a ground-test facility, some method of preheating the flow is necessary. The reason for this is the result of a high-speed aerodynamic phenomenon. As the Mach number of a gas increases, the static temperature of the gas decreases. 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 of a scramjet engine, because the temperature and pressure spike of the detonation wave will not be great enough to ignite the cold fuel-air mixture. Thus, the mixture must be preheated to hotter temperatures in order to achieve detonation in the combustion chamber.

Preheating air in scramjet engines 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. The latter method is popular because of its relatively low cost, low risk, and wide-operating range. In this method, a conventional combustor is placed upstream of the scramjet inlet. The combustor produces hot gases that mix with cold air, resulting in temperatures necessary to simulate hypersonic flight conditions. A disadvantage of this ground-testing method, however, is that the chemical composition of the vitiated air does not match the composition of the clean air that the scramjet engine would intake during normal flight [1]. The objectives of the proposed research are twofold: (1) design a vitiated-air heater to simulate the inlet conditions necessary for hypersonic flight and (2) investigate the effects of the vitiated air heating on supersonic combustion via detonation.

Selected Literature Review

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.

Huellmantel et al. [3] 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 standard 90° V-gutter. Some of the shapes 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 a ramp. 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 ramp 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.

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

Turns [4] explains fundamental differences between detonations, shocks, and deflagrations; and then reviews methods for estimating detonation velocities. Detonation waves are related to shock waves in that the energy released by igniting the combustible mixture sustains the shock wave. Flow downstream of normal shocks is always subsonic, whereas flow downstream of detonations is locally sonic. Deflagrations propagate much more slowly than detonations, and cause an increase in velocity across the deflagration. Like shock waves, static pressure spikes across the detonation, whereas it remains essentially constant across the deflagration. The only similarity between detonations, shock waves, and deflagrations is that static temperature rises across the wave.

Chapman [5] 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 [6] developed a more exact formula to the detonation velocity. Gordon and McBride [7] approached the solution numerically by writing a computer program that calculates detonation parameters. In this program, which is widely used today for detonation research, 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 will be used in the design and investigation of the vitiated air heater.

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.

Edelman and Spadaccini [8] conducted a theoretical investigation of the effects of vitiated-air heating in hypersonic airbreathing engines and made several key conclusions. At hypersonic conditions, water vapor from hydrogen vitiation may condense, and 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 psia, 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 either increase or further decrease this delay time.

Methodology

The proposed research will be conducted at the Propulsion and Energy Research Laboratory at the University of Central Florida. As stated previously, the research objectives are (1) design a vitiated-air heater (VAH) to simulate the inlet conditions necessary for hypersonic flight and (2) investigate the effects of the vitiated-air heating on supersonic combustion via detonation. To satisfy these objectives, the investigation will consist of three experimental techniques: temperature measurements via thermocouples, flow visualization via Schlieren photography, and velocity measurements via a pitot tube.

To simulate hypersonic flight conditions to ground test the scramjet engine, the pressurized air must be heated to over 1300 K. To achieve this, the hot gases from the VAH will mix with room temperature air from the pressurized tanks. After passing through the mixing chamber, the vitiated air will be expanded through a nozzle. To determine if the 1300 K goal has been met, a thermocouple will be placed in the exhaust stream of the nozzle. The presence of shock waves in the vicinity of the nozzle will need to be assessed before analyzing the temperature measurements.

Flow visualization via Schlieren photography is necessary for two reasons: to determine the degree to which the hot and cold streams mix and to assess the presence of shock waves. Because hot and cold gases at the same pressure will differ in density, pockets of each will show up on the photographs if mixing is insufficient. The mixing chamber may need to be extended in this case. A shock pattern in the mixing chamber would be an undesired consequence of hot gases exhausting out of the VAH at too high of a pressure. A shock wave at or near the exit plane of the nozzle is expected and, again, its location is important in analyzing temperature measurements.

Measurements from a pitot tube downstream of the nozzle exhaust are important in determining whether the hypersonic flow conditions have been achieved. They will also be used in conjunction with the temperature measurements.

Preliminary Investigation

Before design and investigation of the vitiated-air heater (VAH), the following calculations were necessary.

- To match the scramjet inlet Mach number to the detonation Mach number, the fuel-air mixture at the inlet will need to be at static temperatures of 225-275 K and equivalence ratios of 0.5-1.0.
- Using isentropic relations, air flowing at Mach 5 will have a total temperature that is six times greater than its static temperature.
- Approximately 165 g/s of vitiated air at 1350 K will need to flow through the scramjet nozzle. If stoichiometric hydrogen in air combusts at 2458 K, then the VAH will need to exhaust 80 g/s of burnt gases to be mixed with 85 g/s of room temperature, clean air.
- The fuel-to-air ratio of a stoichiometric hydrogen-air mixture is 0.0292. Thus, of the 80 g/s in the VAH, approximately 77.7 g/s will be air and 2.3 g/s will be hydrogen.
- It is likely that the injection rates of air and hydrogen will need to be adjusted. Figures 1 and 2 on the next page show the possible flow rates at specified pressures and choking diameters.

Figure 1: Air Mass Flow Rates

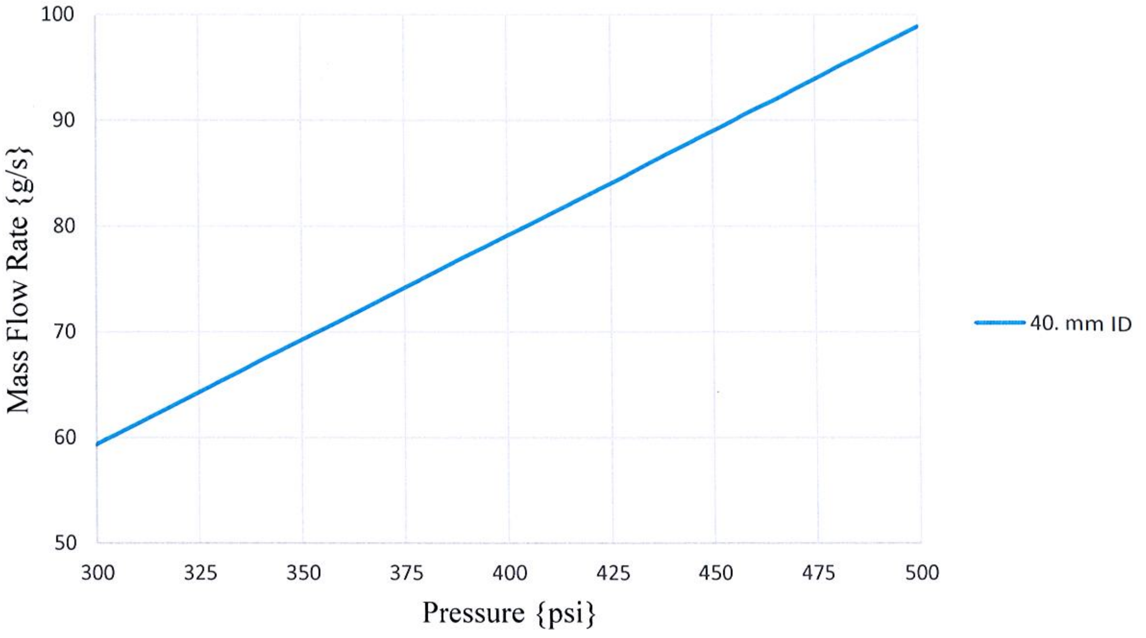
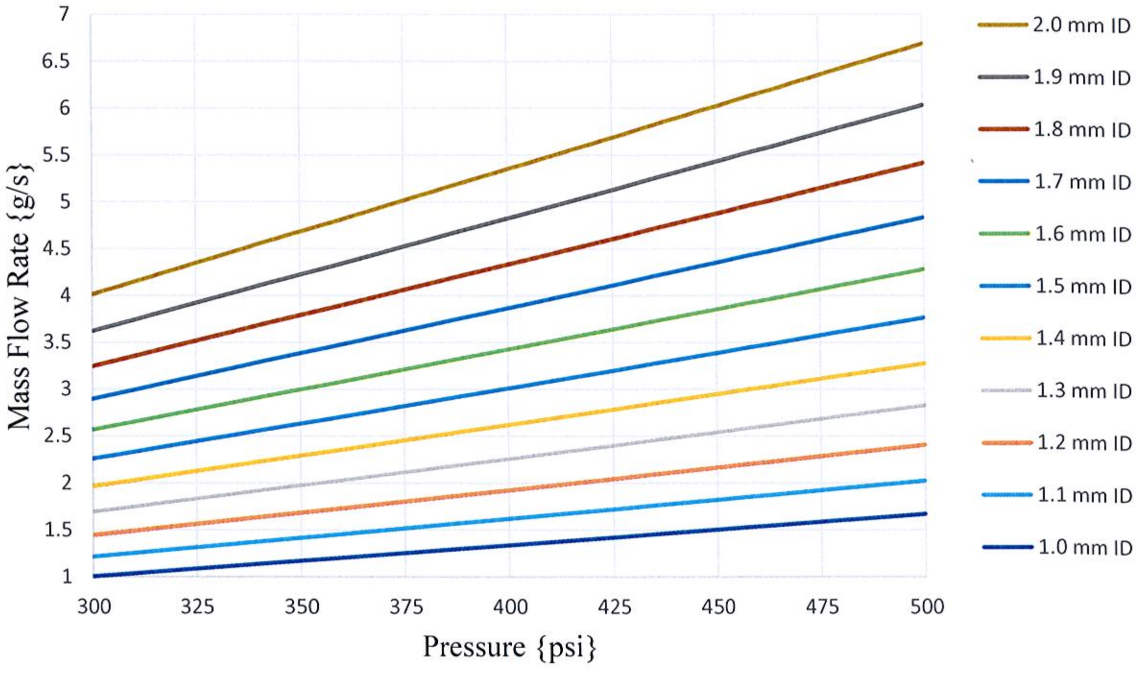


Figure 2: Hydrogen Mass Flow Rates



References

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

[2] Sislian, J. P. "Detonation-Wave Ramjets." *Scramjet Propulsion*. By E. T. Curran and S. N. B. Murthy. Reston, VA: American Institute of Aeronautics and Astronautics, 2000.

[3] 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.

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

[5] Chapman, D. L., "On the Rate of Explosion of Gases," *Philosophical Magazine*, 47: 90-103 (1899).

[6] Kuo, K. K., *Principles of Combustion*, Wiley, New York, 1986.

[7] 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.

[8] 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.