Experimental Investigation of a Pipe-connected Solid Fuel Scramjet in an Arc-heated Facility

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Abstract

A work in progress of static, connected firings of solid fuel scramjet engine is presented. An arc-heated facility is used to heat the air to simulate the flying conditions. The envelope calculations of this heater are shown. A two-dimensional design of an engine with polyethylene fuel, a cooled bottom base and a transparent top cover is presented. Experiment plan for flight Mach number 5.5 at five different altitudes is presented.

1. Introduction

Ramjet engines are the simplest form of air-breathing engines. The operation mode consists of aerodynamic compression in the inlet, addition of energy in the combustion chamber and expansion through the nozzle. In ramjets, the combustion is subsonic. While these engines require an accelerator in order to start operating, they are simple, do not have moving parts and are a lucrative option for supersonic propulsion.

Ramjets are considered a viable propulsion option up to flight Mach 4-5 [1]. For higher Mach numbers the option of ramjet becomes problematic. This happens mostly due to the fact that slowing the incoming air flow to subsonic velocities greatly increases the static temperature of the flow, thus limiting the amount of heat that can be added to it. The solution to this problem is to use scramjets – supersonic combustion scramjets. As the name implies, scramjets are ramjets in which the airflow remains supersonic and the combustion is done in supersonic regime. In this case, the temperature increase is not large enough to negate the heat addition and positive or neutral thrust is theoretically possible.

Due to the different character of the combustion, the scramjet engine is structured differently than a ramjet engine [2]. In the ramjet engine a normal shock is present, while in the scramjet it is absent to keep the flow supersonic. In the ramjet engine, a choked converging-diverging nozzle is present in order to accelerate the flow to a supersonic velocity, while in the scramjet the nozzle is diverging-only and chocking is to be avoided. In most scramjet designs, the separation between the combustion chamber and the nozzle is artificial – usually one diverging chamber is used both as combustion chamber and the nozzle.

Most of the research on scramjet engines is done on liquid scramjets. In a liquid scramjet engine, a liquid fuel such as hydrogen or a hydrocarbon is injected into the combustion chamber and is burned with the flowing air. One of the biggest problems that liquid scramjet face is the very short residence time of the fuel in the combustion chamber – usually lower than 5 ms [3]. This creates a set of atomization, ignition and combustion problems that are extremely difficult to solve. Most of the research on liquid fuel scramjet uses hydrogen as a fuel for this reason. Having said that, the US Air Force has achieved a sustained supersonic combustion of a hydrocarbon fuel at the last test of its X-51 scramjet program [4]. This success, however, was preceded by several unsuccessful attempts to use hydrocarbons as fuel.

One of the least explored concepts of scramjets is the solid fuel scramjet (SFSJ). In this case, the fuel is a solid grain and the supersonic air flows through it. The high temperature of the flow usually ignites the fuel and combustion is sustained. Some of the problems of the supersonic combustion that are encountered in the liquid case, are absent in the solid case – such as atomization, for example. The more important advantage of SFSJ is the fact that the research and understanding of the phenomena of scramjet operation and combustion are performed on fuels that are, or resemble well, practical fuels. Not a lot of research was done about SFSJ and many works in the area were done at the Technion – Israel Institute of Technology [5,6,7,8].

When designing the combustion chamber of SFSJ, two major related aspects need to be considered. The first is the sustainability of the flame and the second is the aerodynamic aspect of the flow acceleration. After several iteration by different authors [9,10,5] the schematics in Figure 1 were obtained as the optimal configuration.

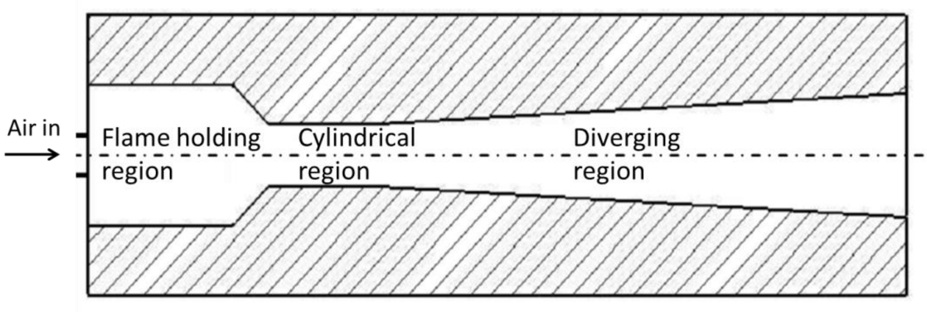

Figure 1. The schematics of the combustion chamber of SFSJ[5].

The engine is divided to three regions. The first is the flame holding region. The inlet is a back-facing step, in which recirculation that serves as flame holder is present. The second region is the cylindrical region. Its radius is smaller than the radius of the flame holding region, but larger than the radius of the inlet. The reason for the presence of the cylindrical region is to prevent a too fast acceleration of the flow, which can lead to the extinction of the flame. The reason for the cylindrical region to be larger than the radius of the air inlet is to prevent thermal chocking of the hot flow. Thermal chocking remains a problem downstream, and this is the reason for diverging region that follows the cylindrical section. The diverging angle is about 3^o and it is introduced to keep the Mach number approximately constant with the increasing heat addition along the engine.

Conducting experimental investigations of scramjet engines is a challenging endeavour. A free jet experiment is the most desired configuration, however two main difficulties prevent using it in many cases. The first difficulty lies in achieving a jet at hypersonic velocities. The second is that a free jet experiment requires a carefully designed inlet, which makes the preparation for the experiment even more complicated and adds another uncertainty to the system. Having said that, some free jet investigations of scramjet engines have been performed [11,12].

A common alternative to free jet experiments is the connected pipe experiment. In this configuration, the air is brought to conditions that simulate the conditions at the entrance to the combustion chamber in a real engine. After that the air is fed to the combustion chamber, thus bringing it to the conditions of the flight without the complexities of the free jet experiment. The downside of this approach is that it requires use of models for inlet behaviour if actual flight conditions are required.

In most cases the air is brought up to the desired conditions using a vitiated (combustion-based) air heater. This was the case in the experiments conducted in the Fine Rocket Propulsion Center at the Technion until now – either an ethylene or hydrogen heaters were used. Vitiated air heaters have two disadvantages. The first is that the air that flows into the combustion chamber is contaminated by combustion products. Though oxygen is added to the mixture to bring it to the molar concentration to simulate air, still a non-contaminated air flow would be more desirable [13]. The more important disadvantage is the relatively limited operation envelope – the air is usually heated to temperatures not exceeding 1500K.

Recently, an effort has been made to bring back to operational mode the arc heater facility at the Aerothermodynamics Laboratory at the Technion. One of the research programs at the facility is the expansion of the SFSJ program. The heating of the air with an electric arc allows air reaching higher temperatures, while not changing the composition of the air. In this paper work in progress is presented. An experimental envelope that the arcjet facility allows is discussed, the design of the experimental system of a two-dimensional SFSJ transparent engine is shown, and the experimental plan is presented.

2. The experimental setup.

2.1 The arc heater.

Arc heaters are devices that can produce high-temperature gas and plasma streams for extended period of time (up to several minutes) by passing cold air through and electric discharge established between electrodes of an arc chamber. A typical arc-heater test device consists of an arc chamber, which acts as a pressure and enthalpy reservoir, a plenum gas relaxation section, a convergent-divergent nozzle to give uniform, shock-free flow at the desired speed, a diffuser and an exhaust plant.

The arc-heater at the Aerothermodynamics lab at the Technion (Figure 2) is includes copper annular segments, electrically isolated each from another by ceramic thin discs. Every copper slice is cooled separately by a water circulation system. The segments are tied together to form a cylindrical isolated section of 1 inch-diameter. The plasma heater is made of several sections (each of one is 18 cm long) forming a cylinder. The number of sections in use depends on the heating power required for any specific experiment. An annular cathode is installed upstream (a copper cathode/anode is used for air heating, a tungsten one can be installed when heating inert gases). Next to the cathode an injection section supplies the air/gas to the heater (PGI, principal gas injector), through choked tangential holes. The tangential injection results in a circular motion of the airflow, which contributes to the stability of the electrical arc. Downstream an annular anode is installed. Conduction coils are wrapped around the anode and cathode to form a magnetic field, which attaches the electrical arc to the electrodes and makes it swirl.

Maximum power consumption of the heater is 5MW. The maximum total enthalpy that can be obtained in the heater is 10 MJ/kg. The air flow usually can be sustained at up to 0.5 kg/sec of air with the pressure in the heater chamber of up to 25 atm.

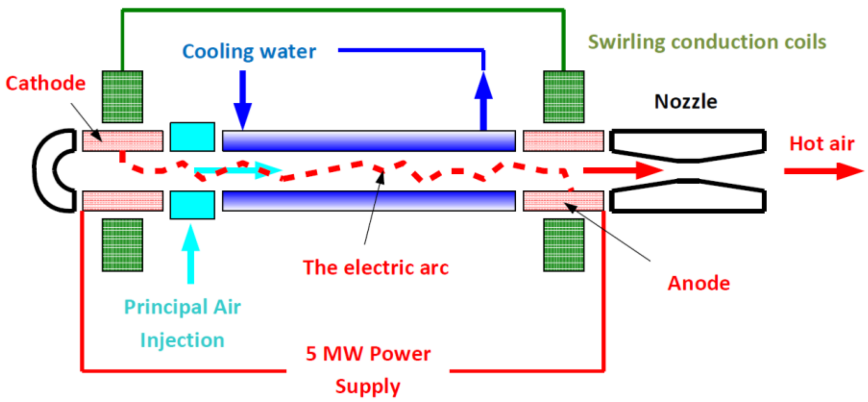

Figure 2. Schematic description of the acr heater.

2.2 The solid fuel scramjet engine.

In this work it was decided to use a two dimensional configuration of the scramjet engine. Two main reasons were behind this decision. The first was that the two dimensional configuration is considerably more simple to attach at the hot air exit of the arc heater facility. The second reason was that it allowed an easier operation of line-of-sight measuring equipment, such as optical pyrometer.

The engine consists of four main parts. The first two are the fuel inserts that form the combustion chamber outline. The fuel is polyethylene. The third part is the engine bottom base, water-cooled and made of steel. The last part is the top transparent cover plate made of quartz. The general overview of the engine can be seen in Figure 3.

The fuel inserts construct an engine of a form that is similar to the engine shown in Figure 1, with two main differences. The first difference is that the engine is two dimensional. The second difference is a result of a different heater configuration. In our case, the dimension of the heater nozzle is 25.4mm x 22.9mm, with the latter being analogous to the exit radius of the heater nozzle in the case of an axisymmetric engine. To compare, the diameter of the nozzle at the entrance to the combustion chamber in the work of Ben-Yakar et al. [5] was d_{in} = 12.45 mm. This required increasing the dimensions of the engine. Figure 4 shows the dimension of the motor (all dimensions in mm). The width of the motor is 25.4 mm.

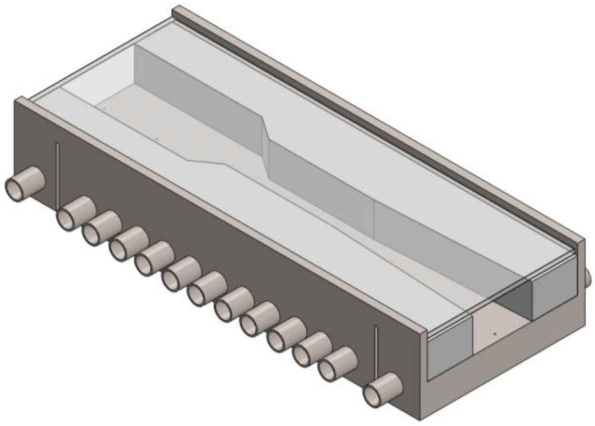

Figure 3. Overview of the SFSJ in current work.

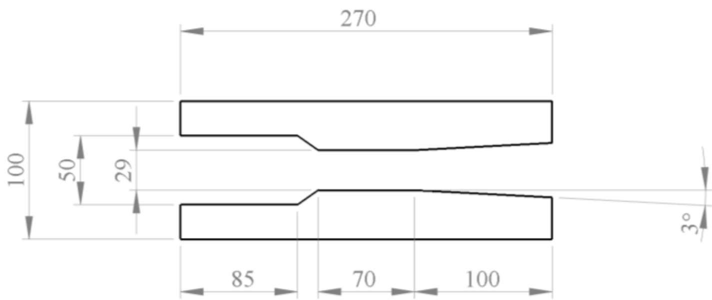

Figure 4. Scheme of the combustion chamber.

The fuel inserts have placement extensions on their bottom part. These are inserted into matching slots in the base plate and are designed to lock the fuel inserts in place and to prevent movement during the experiment. They are cubes with a side dimension of 10 mm. They are located 30 mm from the front and the rear end of the fuel insert. Figure 5 shows the bottom part of the engine with the inserts visible.

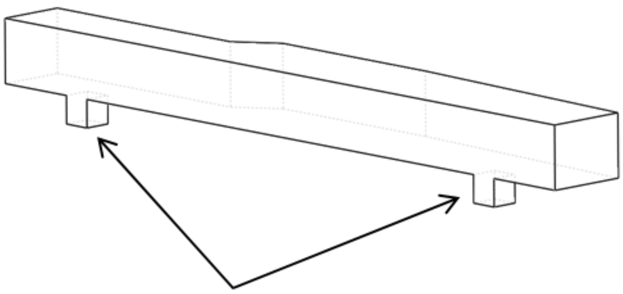

Figure 5. Bottom part of the fuel inserts with placement extensions visible.

The engine bottom base is the host of the engine. It is made out of steel and is water cooled by 13 water tubes. The base has four cubical rectangular slots on its sides to accommodate the fuel. It also has eight small (d_p = 1 mm) through holes on the centerline for pressure measurement. In previous experiments the holes for pressure probes were made in the fuel itself; however a two-dimensional configuration allows to measure pressure without creating imperfections in the engine. At the top part of the engine base there is a slot to accommodate the top transparent plate. On the side ribs of the engine base there are slots for the flexible rack connection (not shown in this paper). This connection allows small movement of the engine, thus enabling thrust measurement. Thrust is measured by a Futek LLB250 button load cell that is attached to the front wall of the engine base. Figure 6 shows the bottom base plate.

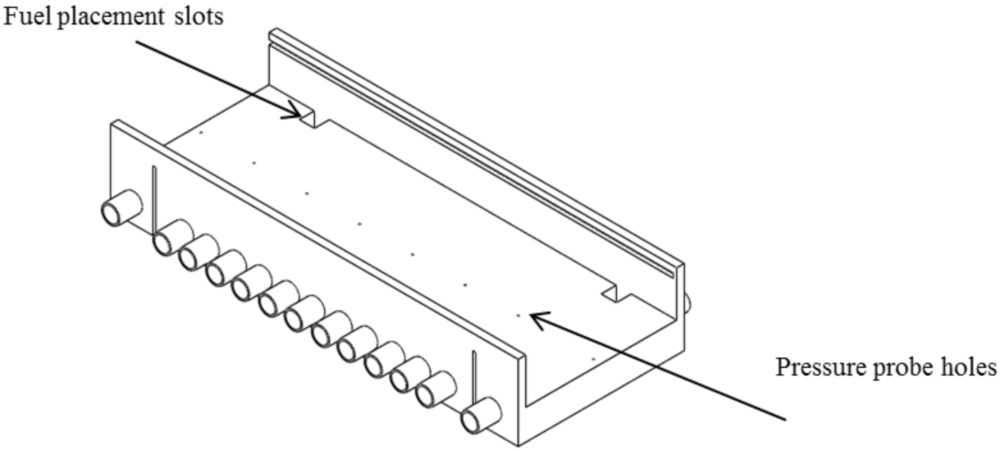

Figure 6. Scheme of the engine bottom base.

The engine is located 2 mm from the heater nozzle exit. Usually, a connected experiment would be rigidly connected to the heater. However, it proved to be problematic in our case for two reasons. Firstly, if the engine is connected physically to the heater, then thrust is measured by the displacement of the whole assembly. In our case it is not achievable. Secondly, the character of the experimental procedure makes fully connected configuration very challenging. In the experiment, the desired work point is achieved by exposing a calibration assembly to the hot flow, and varying the parameters of the heater accordingly to the readings. Once the desired working point is achieved, the calibration assembly is removed from the hot flow, and the working assembly is inserted.

The top transparent plate is a simple rectangular plate that is slid to its place and is made of quartz. The transparency of the top cover allows using optical measurement devices. Currently it is planned to use optical pyrometer to measure the temperature, and fast camera to study the regression rate and if possible – the flame structure. Quartz is a borderline choice – its melting temperature is lower by about 200 degrees than the expected adiabatic temperature of the flame; however, we estimate that the actual temperature is going to be lower, both due to the inefficiencies of the engine and due to the extraction of heat from the system by cooling the lower part of the engine. Therefore, it was decided to use a quartz plate. In the case of quartz being inadequate, a sturdier, partially transparent top plate will be designed using more advanced materials.

3. The experimental conditions

3.1 The operation envelope.

In order to determine the work point of the arc heater, two variables are needed – the total enthalpy of the heater and the mass flow rate (or total pressure). First, let us look at the enthalpy. The airflow around a vehicle flying with a velocity v_a has a stagnation enthalpy h_0 of the following form:

$$h_0 = C_p T_a + \frac{v_a^2}{2} \tag{1}$$

Where C_p is the specific heat capacity at the air temperature T_a. The velocity can be expressed in the terms of flight Mach number M_a:

$$v^2 = M_a^2 \gamma R T_a \tag{2}$$

Here γ is the ratio of the specific heats and R is the gas constant of air. Therefore the total enthalpy can be expressed as following:

$$h_0 = T_a \left(C_p + M_a^2 \gamma R \right) \tag{3}$$

Once the altitude and the Mach number are decided upon, the required total enthalpy of the act heater can be easily determined.

In order to determine the pressure of the arc heater assumptions about the inlet are needed for the conditions at the entrance of the combustion chamber. First, the total pressure recovery in the inlet needs to be estimated. There are two models that we consider for this. The first is the model of Billig [14]. It states that the total pressure recovery at the inlet has the following form:

$$\frac{P_{02}}{P_{0a}} = \left(-8.4 + 3.5M_a + 0.63M_a^2 \right) \frac{\left(1 + \frac{\gamma - 1}{2} M_2^2 \right)^{\gamma/\gamma-1}}{\left(1 + \frac{\gamma - 1}{2} M_a^2 \right)^{\gamma/\gamma-1}} \tag{4}$$

The second model is the SCCREAM [15] model that has the following form:

$$\frac{P_{02}}{P_{0a}} = 0.0015741M_a^3 - 0.032917M_a^2 + 0.10146M_a + 0.81841 \tag{5}$$

The Mach number at the combustion chamber entrance M_2 is assumed to be M_2 = 0.4M_a in the Billig [14] case and the following relation for the SCCREAM [15] model:

$$M_2 = -0.005M_a^2 + 0.4179M + 0.3927 \tag{6}$$

From this the determination of the flight condition is clear. The M_2 is determined by the nozzle of the heater. M_2 allows determining the flight Mach number. The pressure in the heater, P_{02} can be determined from the following relation:

$$P_{02} = P_a \frac{P_{0a}}{P_a} \frac{P_{02}}{P_{0a}} \tag{7}$$

Where P_a is the atmospheric pressure at the desired altitude. The relationship P_{0a}/P_a is taken from the isentropic flow equations for the given flight Mach number. After P_{02} is determined, the mass flow rate can be calculated. It is important to mention that for calculations relevant to flight conditions (like P_{0a}/P_a), γ = 1.4 should be used, but for heater related calculations, a lower value of γ should be used. The exact value is temperature dependent and can be obtained from the relevant tables [16].

From this, an operation envelope of the heater can be estimated. Enthalpy limit of 10 MJ/kg caps the maximum flight Mach number that can be achieved. Assuming that the flight is performed on high altitudes, where the temperature changes are low, Eq. (1) shows that flight Mach number of 10.5 can be achieved. If a flight at sea level is assumed, the highest flight Mach number drops to 9.1. However, scramjets are not intended to fly at such low altitudes, so M_a = 10.5 is the more relevant number.

Pressure limitation provides the lowest flight altitude that can be simulated. The maximum P_{02} that can be reached is 25 atm. P_{02} is calculated from Eq. (7) for each altitude, and the limiting altitude is the one at which P_{02} = 25 atm. Figure 7 shows the operation envelope of the heater for both total recovery pressure models. The region above the lines is the flight conditions that can be simulated. Comparing with the vitiated heaters used previously [6], we can see that the arc-heater in the present work does not provide as good altitude coverage due to lower pressure achievable, but the Mach number range is much higher.

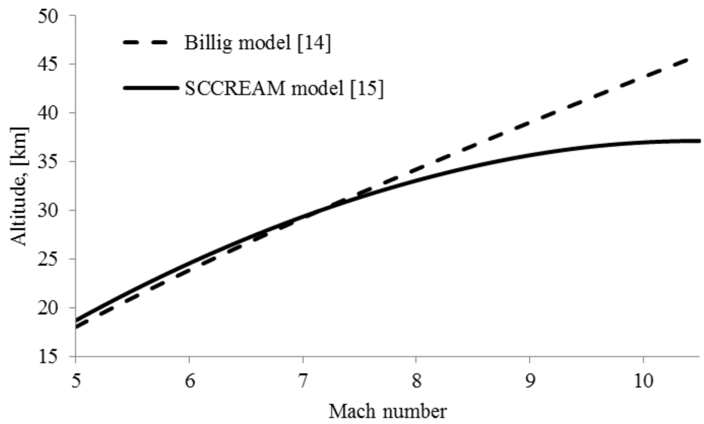

Figure 7: The operation envelope of the heater. The conditions above the lines can be simulated.

3.2 The experiment plan

The experiments are expected to be conducted in few months time. The arc heater is equipped with a two-dimensional nozzle that provides Mach number M_2 = 2.2 at the entrance of combustion chamber, thus simulating a flight of M_a = 5.5. Flight at five altitudes will be tested – h = 40,35,30,25 and 20km. Thrust, pressures along the combustion chamber, and combustion temperature at the recirculation chamber will be measured. Also, fast camera will be used to take measurements of the regression rate and provide a general visual insight to the process.

4. Conclusions

A work in progress of a connected solid fuel scramjet combustor with polyethylene fuel is presented. This work has two new aspects relatively to previous research efforts at the Technion. Firstly, a new, electric-arc based, heater is used. This allows expanding the test envelope relatively to the previous experiments and using a purer air than in the case of vitiated air heater. Secondly, a two-dimensional engine with transparent top cover is presented. This allows simple line-of-sight optical measurements. The experiments, that are expected to be conducted in the near future, are static firing experiments that simulate flying conditions of M_a = 5.5 at different altitudes.

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