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Proceedings of the Combustion Institute 30 (2005) 2481–2488
Proceedings of the Combustion Institute
www.elsevier.com/locate/proci

Catalyzed combustion of hydrogen–oxygen in platinum tubes for micro-propulsion applications

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Abstract

The present investigation addresses the need to understand the physics and chemistry involved in propellant combustion processes in micro-scale combustors for propulsion systems on micro-spacecraft. These spacecraft are planned to have a mass less than 50 kg with attitude control estimated to be in the 1–10 mN thrust class. Micro-propulsion devices behave differently than macro-scale devices because of the differences in magnitude of flow rates and heat transfer. Reducing the combustor size increases the relative surface area, increasing the heat loss, and as combustors are continuously reduced in size, they approach the quenching dimensions of the propellants. Combustors of this size are expected to significantly benefit from surface catalysis processes. A miniature flame tube apparatus is chosen for this study because microtubes can be easily fabricated from known catalyst materials, and their simplicity in geometry can be used in fundamental simulations for validation purposes. Experimentally, we investigated the role of catalytically active surfaces within 0.4 and 0.8 mm internal diameter microtubes, with special emphases on ignition processes in fuel rich gaseous hydrogen and gaseous oxygen. Calculations of flame thickness and reaction zone thickness predict that the diameters of our test apparatus are below the quenching diameter of the propellants in most atmospheric test conditions. The temperature and pressure rise in resistively heated platinum microtubes and the exit hydrogen concentration were used as an indication of exothermic reactions. Data on imposed heat flux/preheat temperature required to achieve ignition versus mass flow rate are presented. With a plug flow model, the experimental conditions were simulated with detailed gas-phase chemistry and surface kinetics. Computational results, in general, support the experimental findings.

Keywords: Catalytic combustion; Micro-propulsion; Micro-combustor

1. Introduction

In recent years, the trend has been to develop smaller sizes of spacecraft. The driver for this need of smaller spacecraft comes from both the scientific and military communities. New classes of spacecraft called micro-spacecraft have been defined by their mass, power, and size ranges [1]. Spacecraft in the range of 20–100 kg represent the class most likely to be utilized by most small satellite users in the near future. There are also efforts to develop 10–20 kg class spacecraft, defined as "nano-spacecraft," for use in satellite constellations [1]. In addition, mission designs employing formation flying maneuvers, which would require a level of control only available by a micro-

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doi:10.1016/j.proci.2004.08.203

thruster class, are currently in the process [2]. More ambitious efforts will be to develop spacecraft less than 10 kg, in which Micro Electrical Mechanical Systems (MEMS) fabrication technology is required [1]. These new micro-spacecrafts will require new micro-propulsion technology.

Although micro-propulsion includes electric propulsion approaches, the focus of this paper is micro-chemical propulsion. Micro-chemical propulsion for small spacecraft can be used for primary thrust, orbit insertion, trajectory-control, and attitude control. Grouping micro-propulsion devices in arrays will allow their use for larger thrust applications. By using an array composed of hundreds or thousands of micro-thruster units, a particular configuration can be arranged to be best suited for a specific application. Moreover, different thruster sizes would provide for a range of thrust levels (from μN's to mN's) within the same array. These arrays of micro-propulsion systems would offer unprecedented flexibility and redundancy for satellite propulsion and reaction control for launch vehicles [1].

Although the field of micro-propulsion is new, several micro-scale chemical propulsion devices have been developed [cf. 3]. In terms of using MEMS technology, a high-pressure bi-propellant micro-rocket engine is already being developed [4]. High pressure turbopumps and valves are to be incorporated onto the rocket "chip." High pressure combustion of methane and oxygen in a micro-combustor was demonstrated without catalysis, but ignition was established with a spark. This combustor has rectangular dimensions of 1.5 mm × 8 mm and a length of 4.5 mm, and was operated at 1.25 MPa with plans to operate it at 12.7 MPa. These high operating pressures enable the combustion process in these devices, but these pressures are not practical for pressure-fed satellite propulsion systems. Note that the use of these propellants requires an ignition system and that the use of a spark would impose a size limitation to this micro-propulsion device because the spark unit cannot be shrunk proportionately with the thruster.

It is, in general, recognized that reduced-scale versions of the conventional systems will not be practical for micro-satellites. As combustors are scaled down, the surface-to-volume ratio increases. The heat release rate in the combustor scales with volume, while heat loss rate scales with surface area. Consequently, heat loss eventually dominates over heat release when the combustor size becomes smaller, thereby leading to flame quenching. The limitations imposed on chamber length and diameter have an immediate impact on the degree of miniaturization of a micro-combustor. Before micro-combustors can be realized, such a difficulty must be overcome. One viable combustion alternative is to take advantage of surface catalysis.

Catalyzed ignition/combustion using miniature tube apparatus, which is fabricated from known catalyst materials, is proposed herein. The simplicity in microtube geometry facilitates fundamental simulations to compare with measurements for validation purposes. Once catalyzed ignition is established in a microtube, the reacting gases can be used for propulsion in the micro-propulsion device or they can be propagated into the combustion chamber for ignition in larger thrust class rockets. This would benefit all rocket propulsion systems through the elimination of high voltage electrical discharges for spark ignition.

Results presented in this paper consist of an experimental evaluation of the minimum catalyst temperature for initiating/supporting combustion in sub-millimeter diameter tubes, whose geometries approach or are smaller than the flame thickness of the propellants. The tubes are resistively heated, and reactive premixed mixtures are passed through the tubes. Tube temperature, inlet pressure, and exit mixture composition are monitored for an indication of exothermic reactions and composition changes in the gases. Hydrogen/oxygen mixtures of low mixture ratios (high equivalence ratios) flowing in platinum tubes are tested herein. Fuel rich conditions are selected to avoid melting of the catalyst and oxidation loss of catalyst material. Each of these chemicals is non-toxic and can be produced in orbit by water electrolysis [5]. Detailed gas chemistry, thermodynamic properties, transport properties, and surface kinetics for $H_2/O_2/Pt$ system are also available for simulating the experimental conditions.

Although preliminary results at low pressure (~0.34 atm) using an altitude test facility have been reported in [6], this paper will focus on the atmospheric pressure tests. The performance goal for the present bipropellant micro-thruster is 300 s of specific impulse. As such, the flow rates representative in the experimentation, 0.00034–0.0034 g/s of propellants, will generate the 1–10 mN of thrust required for the micro-spacecraft. In the following, we will sequentially present the characterization of gaseous H_2/O_2 combustion, experimental setup, computational methodology, and results and discussion.

2. Flame characteristics and quenching diameter

The so-called quenching diameter is the critical diameter of the tube below which flame propagation is not possible. Theoretical analysis has shown that the quenching diameter is of the same order as the flame thickness [7]. Spatially resolved profiles of temperature and heat release rate for a freely propagating H_2/O_2 flame in the flame coordinate were computed using PREMIX [8]. The H_2/O_2 kinetic mechanism was taken from [9].