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Research article

Flow stabilized porous heterogeneous combustor. Part I: Design and development

Anthony Carmine Terracciano [a,*], Samuel De Oliveira [a], Manuel Robayo [a], Subith S. Vasu [a,b], Nina Orlovskaya [a]

[a] Deparment of Mechanical and Aerospace Engineering, University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816-2450, USA
[b] Center for Advanced Turbomachinery and Energy Research (CATER), University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816-2450, USA

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ABSTRACT

A heterogeneous combustor was developed where the flame position within the ceramic porous media, contained within the combustor, could be controlled using the reactant flow rate. The porous media within the combustor can be coated with a catalyst to further promote combustion; this apparatus was designed to enable the investigation of various catalysts to be evaluated for their effectiveness as promoters of combustion. A unique feature of the combustion chamber showcased within this work is that the position of the flame is controlled by flow rates rather than the conventional method of flame arrestors, minimizing pressure drop across the combustion chamber. The developed operational system consists of six well-integrated and interconnected parts: the combustion chamber, a reactant storage and metering system, the reactant delivery nozzle, the exhaust sampling port, an externally located microphone, and a CCD camera. Within this present work Al_2O_3 porous media of 10 ppin was used during the initial testing of the developed system.

1. Introduction

Current Combined Heat and Power (CHP) technologies are becoming a popular means of satisfying the ever growing thermal and electrical energy demands. Most CHP systems around the world are located at large facilities, from agriculture farms to universities and manufacturing plants [1], with the systems providing power having an output in excess of 1.5 kW. Such CHP units demonstrate promising energy and cost savings for end users. For example Kaiser Medical Center in Vacaville, CA saw significant annual savings within three years of installing their 750 kW microturbine CHP system, and the University of Arizona in Tucson benefited tremendously from a 12 MW CHP system that meets 25% of its electrical load. There are also "micro"-CHP systems available in the market (Table 1) that provide 1–5 kW of power. However, even smaller CHP units that provide <1 kW of power have yet to be widely explored or researched. One such CHP unit was developed in [2] that was based on superadiabatic porous media combustion, as a cheap heat and power source. Heat is released by burning an ultra-lean, low calorific fuel/air mixture within a highly porous silicon carbide (SiC) matrix. The heat produced by such superadiabatic combustion [3] can be directly extracted and can also be converted to electric power using attached thermoelectric modules, which are capable of generating up to 3 W of electric power, sufficient to power cell phones or other small electronic devices. A schematic presentation and a photograph of the aforementioned CHP unit in operation is shown in Fig. 1. The CAD schematic along with temperature distribution profile are shown in Fig. 1A and B. The insert in the Fig. 1C shows the instantaneous electric power output during operation. As one can see from Fig. 1 the transparent quartz window enables the flame and the high temperature porous solid media to be visible, enabling the device to efficiently radiate heat. The flame is used to provide a thermal gradient for the hot surfaces of 12 thermoelectric modules placed on the sides of the combustor. Aluminum heat sinks attached to the outer surfaces of the thermoelectrics, passively dissipate heat to the surroundings. Such heat dissipation enables a larger temperature gradient between "hot" and "cold" surfaces of the thermoelectric modules, improving both its efficiency and electric power output.

In heterogeneous superadiabatic combustion the highly porous ceramic media provides large contact surfaces through which the solid and gas phases interface, thus enabling appreciable heat transfer between them [4]. A mixture of gases as they pass through the pores of the solid become highly turbulent [5], enabling efficient and rapid dispersion of molecular species in the gas phase. The solid phase within the combustion chamber provides high thermal conductivity and emissivity compared to gases, facilitating heat transfer through the solid. Within the vicinity of peak combustion intensity, heat released is transported through the solid via radiation and conduction toward the unreacted species entering the combustion chamber. Heat within the solid may then be convectively transferred to the incoming reactants, increasing the gas phase temperature without the conversion of chemical energy [6]. Analytical models of heterogeneous combustion using a

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[*] Corresponding author.
E-mail address: antwan718@gmail.com (A.C. Terracciano).

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Table 1
Micro-CHP options.

Size, (kW)	Product name	Prime mover	Country	Manufacturer	Parent company	Installed units
5.3	DACHS	IC engine	Germany	SenerTec	Baxi Group	>8000
5.0	Genelight	IC engine	Japan	Yanmar	–	Unknown
4.7	Ecopower	IC engine	Germany/USA	PowerPlus Technology/Marathon Engine Systems	Valliant	>1400
1.2	WisperGen	Stirling engine	New Zealand	Whisper Tech	–	Unknown
1.0	Ecowill/Freewatt	IC engine	Japan/ USA	Climate Energy	Honda	>10.000

single step reaction mechanism in conjunction with the necessary governing equations for porous media of finite and infinite length are presented elsewhere [7,8]. To contain the flame within highly porous ceramic media immersed within the combustion chamber, flame arrestors such as honeycomb ceramic structures or other reticulated foams with lower porosity were always used which created extra parts in the combustor design [9,10]. While a very low equivalence ratio could be achieved in porous combustor operation [11,12] the reason was a very heavy outside isolation offered by the flame arrestor, which prevented radiative heat loss and provided an interface between the two structures for the flame to stabilize [13]. While such isolation of the combustion chamber enabled stable operation at equivalence ratios as low as $\varphi = 0.026$ [14], the design of the porous combustor became much more complicated and limited its practical use. However, heterogeneous combustion is used in many advanced applications such as the oxidation of volatile organic compounds (VOCs) [15], industrial radiant heaters [16], and the efficient production of syngas from ultra-rich fuel mixtures [17].

To further explore one of the aspects of CHP system operation - heterogeneous combustion, the focus of this paper is on the demonstration of a heterogeneous combustor designed for operation on either gaseous or liquid fuels. The design of the heterogeneous combustor presented within this work is unique as it is the first heterogeneous combustor presented in literature which only utilizes reactant flow rates to control flame position instead of restrictive flame arrestors while using a porous media which does not occupy the entire length of the combustion chamber. This optimized combustor, where no flame arrestors were implemented, minimizes the drop in total pressure across the combustion chamber. By designing the combustor without flame arrestors, the necessary pneumatic head to enable appropriate reactant flow rates is significantly reduced at the cost of an increased minimum equivalence ratio. The combustor is equipped with multiple instrumentation devices including: thermocouples, a CCD camera, exhaust sampling port with a coupled gas chromatograph, and a microphone. Subsequently, the unique design of this heterogeneous combustor provides a test platform for testing various combustion catalysts capable of operating on both liquid and gaseous fuel.

2. Design and development

The operational system of the developed combustor consists of six parts: the combustion chamber, reactant storage and metering systems, the reactant delivery nozzle, the exhaust sampling port, an externally placed microphone, and the CCD camera. Three primary sections (a) the combustion chamber with 13 thermocouples mounted along the length of the porous media and at the inlet and at the combustion exhaust, and (b) a reactant delivery and metering system, and (c) reactant delivery nozzle are the most important parts of the developed system and will be first described in great detail. After fuel/air gases mixture is delivered and combustion reactions occurred within combustion chamber, there is an exhaust sample port, which enables gases from the combustion environment to be discharged. In addition to discharging combustion byproducts, the exhaust provides three additional functions: (i) to enable gases from the combustion environment to be drawn in to a gas chromatograph, (ii) to allow for acoustic emissions to be recorded via an external microphone, and (iii) to enable visible radiative emissions from the ceramic media at the exhaust side of the combustor to be recorded using a CCD camera.

2.1. Design and development of combustion chamber

A schematic presentation (2A) and an assembly model (2B), and a photograph of the developed chamber in operation is shown in Fig. 3. Some of the factors that were considered in the design of the combustion chamber were (i) method of ignition, (ii) flow rate limits, and (iii) dimensions of the porous media, and simplicity of design. As one can see from Fig. 2A, the combustion chamber specifically refers to the inner 316 stainless steel cylinder encasing the porous ceramic media. The dimensions of both the chamber and the porous media are also shown in Fig. 2A, as well as the distance between the porous media and combustion chamber inlet. The locations of 13 thermocouples along the length of the combustion chamber as well as two thermocouples placed at the inlet and at the exhaust are also shown, which are used to collect temperature profiles during combustion as a function of time.

The incorporated sapphire viewing windows and stainless steel shutters, which are reflected in the schematic presentation (Fig. 2A), can be used to visualize the temperature distribution on the outer surface of the stainless steel combustion chamber when the shutters are open enabling determination of the approximate location of the flame within the combustion chamber. The photograph taken of the outer surface of the stainless steel combustion chamber radiating heat, through the sapphire window with the front shutter open, reveals the approximate location of the combustion zone as shown in Fig. 3. However, if the stainless steel inner combustion chamber were to be replaced by a sapphire tube, direct flame visualizations or the incorporation of advanced spectroscopy techniques could be made [18].

Fig. 4 presents side view photographs of the combustion chamber, where the Fig. 4A presents the chamber with both top and side shutters closed, and Fig. 4B presents the chamber with the shutters removed revealing the sapphire optical windows, which can be used for observation of temperature distribution inside. The 13 axial combustion chamber thermocouple wire leads are also visible in Fig. 4 A and B and an optical micrograph of a thermocouple built for temperature measurements along the combustion chamber is shown in Fig. 4C. Axially placed thermocouples are positioned 6.87 mm apart within small bores along the outer radius of the combustion chamber axis (Fig. 2A). Each thermocouple is prepared with an alumina double bore tube (AdValue Technology LLC: Tuscon, USA) through which K-Type 30 GA wire (Omega Engineering: Stamford, USA) is drawn. Thermocouple beads are manufactured via spot welding and have a diameter of approximately 700 μm. Each thermocouple within the bore is then exposed indirectly to the combustion environment, which occurs across a SAE 316 stainless steel wire mesh, with each thread being approximately 115 μm in diameter. A schematic of the thermocouple is located relative to the porous ceramic media is shown in Fig. 4D. While all 13 thermocouples were installed for temperature measurements during combustion, for the practical reason the results of the measurements of 5 thermocouples (TC0, TC1, TC2, TC3, and TC4) are typically used for characterization when presenting temperature profiles as a function