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Design and development of a porous heterogeneous combustor for efficient heat production by combustion of liquid and gaseous fuels

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HIGHLIGHTS

- Design scheme for a bi-fuel heterogeneous combustor featuring silicon carbide ceramic media within the combustion chamber.
- Combustor operation of both lean and ultra rich fuel-air mixtures.
- Suggested applications for heterogeneous combustors.

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ABSTRACT

This work focuses on the design and operation of a heterogeneous combustor capable of operating on both gaseous and liquid fuels, featuring a highly porous (up to 90% porosity) silicon carbide ceramic media within the combustion chamber where the combustion reactions take place. Four interlinked devices – a heat exchanger, a vaporization chamber where liquid fuel may be injected, a mixing chamber, and combustion chamber – comprise the flow loop of the combustor. Operation of the combustor is presented using temperatures recorded via thermocouples at various locations in the flow loop as well as along the axis of the combustion chamber. Demonstration of the combustor's ability to operate on gaseous methane and air at a low equivalence ratio of 0.50 is presented across various total flow rates. Additionally, the ability of the combustor to operate on liquid fuel was also verified upon the inclusion of kerosene in the fuel-air mixture.

1. Introduction

A number of energy conversion technologies are being considered as alternative sources of thermal and electrical energy, such as porous heterogeneous combustors [1–4], fuel cells [5–9], thermoelectrics [10–11], photovoltaics [12–15], and solar thermal [16], among others [17–19].

Heterogeneous combustion, in which a solid porous media within the combustion chamber is used to facilitate and control combustion of the fuel-air mixture, is a viable energy conversion technology. When considering heterogeneous combustors, the properties of the porous media significantly impact the performance of the combustor [1]. Performance characterization of the combustor and the theory on heat recirculation within the combustion chamber are also discussed in [1]. Other important considerations when it comes to heterogeneous combustors include flammability limits for various combustors [2], associated length and time scales in the combustion chamber [3], catalytic particle separation [3], and the local thermal and chemical non-equilibriums occurring in the combustion chamber [3]. Heterogeneous combustors are idea candidates in combined heat and power applications, as discussed in [4] in which an 8 kW porous media burner was implemented as part of a domestic combined heat and power unit.

Other emerging energy conversion technologies which complement heterogeneous combustion include hydrogen or methanol powered fuel cells technologies [5]. A detailed review of the principles of operation, types, and numerous applications of fuel cells were discussed in [6]. Direct methanol fuel cells are ideal in mobile applications. Mechanisms related to the methanol crossover in direct methanol fuel cells can be seen in [7]. Solid oxide fuel cells can be scaled to produce power at a large scale and are also very suitable in combined heat and power applications; configurations of multiple solid oxide fuel cells for useful power configurations and modeling behavior of individual cells are presented in [8,9]. Apart from fuel cells, thermoelectrics could also be compatible with heterogeneous combustors. Electric power generation by

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oxide thermoelectrics was discussed in [10], by thin film thermoelectric devices in [11], and by PbTe thermoelectric material in [12].

Although photovoltaics have been around for a long time, this technology is undergoing significant iterations; and can also be used to collect emissions of various wavelengths from the solid media of the combustion chamber. These include emerging efficient photovoltaic technologies [13–15], three dimensional nanopillar array photovoltaics on flexible substrates [13], organic photovoltaics which replace n- and p-type traditional semiconductors for photovoltaic cell applications [14], and various configurations for photovoltaic power systems [15]. Heterogeneous combustors may even be paired with parabolic trough solar collectors for water heating in cold areas [16]. Other notable energy conversion technologies that could be paired with heterogeneous combustion are thermionic systems for power optimization [17,18], piezoelectric materials use for power harvesting [19]. Piezoelectric materials can also be very beneficial if used as sensors to provide real time operational information in heterogeneous combustors [19].

System flexibility, high overall efficiency, low emissions, and potentially low material and manufacturing costs are the most important factors driving these energy conversion technologies forward. These technologies have high importance as they provide clean and efficient energy conversion pathways in the power market for the near future, and they are enabling technologies for improving the energy security in the world.

One of the very promising technologies for efficient and cheap heat production is combustion of lean and ultra-lean fuel/air mixtures within the solid porous matrix [20–22], where fuel content in the mixture could be very minimal with equivalence ratios being as small as 0.1 [23]. While conventional fuel/air burning techniques have defined flammability limits beyond which a flame cannot self-propagate due to heat losses, matrix stabilized porous medium combustion, named as superadiabatic combustion [24], is an advanced technique in which a solid porous matrix within the combustion chamber accumulates heat from the hot gaseous products and preheats incoming reactants. This heat recirculation extends the standard flammability limits and allows burning of ultra-lean fuel/air mixtures, conserving energy resources, and enabling the burning of gases of low calorific value, utilizing otherwise wasted resources. The porous medium facilitates heat transfer via radiation and conduction through the solid phase, from the high temperature combustion taking place within the voids of the porous solid to preheat incoming reactants prior to the reactants crossing into the flame [2,25]. As a result of the distribution of heat the chemical reaction zone becomes rather diffuse, compared to a conventional flame, leading to a more uniform temperature profile. The large surface area to volume ratio of the highly porous media maximizes the contact of the solid with the gas, thus maximizing the heat transfer between gas and solid and allowing temperature in the hot zone to rise [22,26]. The high thermal conductivity and emissivity of the solid facilitates heat transfer through the solid matrix via mechanisms which do not exist in open flame burners. The heat transfer, through the gas phase, is further enhanced both by the dispersion of the reactants flowing through the porous medium and by mixing due to the turbulence from small vortices of gas generated by the solid medium [2,20].

The combustion of ultra-lean fuel/air mixtures, which is easily achieved in superadiabatic combustors, substantially increases the efficiency with which chemical energy of hydrocarbon fuels can be converted into useful power [1]. While using gaseous fuel, such as methane or hydrogen, is a viable option for heat production by superadiabatic combustion, the use of liquid fuel has many advantages such as: higher combustion temperature, greater volumetric power output, and higher energy density in comparison with gaseous fuels. Superadiabatic combustion can be considered to make the combustion process safer since the gaseous mixture is so lean in fuel it cannot burn outside of the porous medium.

Among the existing practical applications of porous burner technology are power generation via thermoelectric devices [27,28], small scale heating purposes [4], combustion of low calorific value landfill seepage gases [29], oxidizers of volatile organic compounds (VOCs) [29,30], and syngas producers [30]. Two novel applications of heterogeneous combustors, which were not considered in the past, are an Organic Rankine Cycle (ORC) generator, and a highly efficient and selective reactor for gas flares at chemical manufacturing plants or oil wells. For the first suggested ORC application, the heterogeneous combustor enables heat extraction via radiation, and if set to operate under ultra lean conditions the heat generated would have a relatively low temperature. Such low temperature heat could be efficiently incorporated into an Organic Rankine Cycle (ORC) generator [31], allowing utilization of working fluids with critical temperatures that are significantly lower compared to the critical temperature of water, which is currently used as a working fluid in most ORCs. For the second suggested practical application of the developed combustor as reactors for gas flares, such reactors can be combined in series and parallel to treat appropriate mass flow rates and selectively target specific chemical reaction channels at chemical manufacturing plants or oil wells [32].

Here we report the results of design and development of a novel porous combustor, in which SiC ceramic material was used as the highly porous media that serves as the medium in which the combustion reactions occur, powered by kerosene as a high energy density fuel and is readily available on the market. The porous combustor was designed and developed so that it could not only operate at different/varying temperatures, but that it could also operate over a wide range of equivalence ratios and volumetric flow rates of the fuel and air mixtures. Another goal was to build a reactor that would allow the authors to investigate the possibility of using different fuels such as in simple hydrocarbons like gaseous methane, or more complex hydrocarbons such as n-dodecane or n-heptane, which are in liquid form under standard conditions.

2. Design and development of bi-fuel porous combustor

The detailed CAD model of the bi-fuel combustor is presented in Fig. 1A and a photograph of the assembled porous combustor ready for operation with the SiC porous media inserted, that is visible through a quartz window along with the attached thermocouples as shown in Fig. 1B. The whole combustion unit consists of four interlinked devices – a vaporization chamber, mixing chamber, combustion chamber, and a heat exchanger, all connected into a single flow loop configuration with a number of control units such as a pump, a primary control valve, a water removal filter, a pressure regulating valve, sensory systems, as well as fuel supply reservoir, among other ancillary components also included as part of the combustor's design (Fig. 2). A simplified block diagram showing the entrance and exit paths of the working fluid is shown in Fig. 3.

2.1. Design and operation of heat exchanger

In order to operate the combustor, the ignition mixture of methane and dried-pressure regulated air is prepared with an equivalence ratio $\phi = 1$ by mixing both gaseous components via a T-junction before they enter the heat exchanger. When the experiments were conducted, the ϕ value was decreased to 0.5, the lowest stable equivalence ratio for a methane-air flame outside of the porous media [33]. The air for the mixture is taken from the air line of the engineering building using a high pressure pump and is then