



## Research Paper

# Surface stabilized combustion technology: An experimental evaluation of the extent of its fuel-flexibility and pollutant emissions using low and high calorific value fuels

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## HIGHLIGHTS

- SSC technology can stabilize a wide range of fuel blends without any modifications.
- The SSC operating modes can be classified by a simple speed ratio.
- The results affirm low emission operation is attainable on all tested gaseous fuels.
- As expected, only trace levels of N<sub>2</sub>O and NH<sub>3</sub> result from steady state operation.
- N<sub>2</sub>O and NH<sub>3</sub> are produced during ignition and near the lean stability limit.

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## ABSTRACT

Surface-stabilized combustion (SSC) is a fuel-flexible technology that extends the stability limits of lean premixed systems, while achieving ultra-low emissions of NO<sub>x</sub>, CO and UHC (unburned hydrocarbons). To evaluate these attributes, the present study quantifies (1) operability characteristics i.e., lean blowoff limit and flashback behavior and (2) pollutant emissions (CO, N<sub>2</sub>O, NH<sub>3</sub>, NO and NO<sub>2</sub>) of a commercial SSC burner when operating at a fixed fire rate on a wide range of fuel compositions. The experimental burner is the Duratherm™ ceramic-fiber burner by Alzeta Corporation. Experiments were carried out with multiple gaseous fuel blends starting with low reactivity biogas blends containing up to 65% CO<sub>2</sub> (by volume) balanced with natural gas, and high reactivity fuels such as hydrogen enriched natural gas (HENG) blends. The burner was able to stabilize multiple fuel compositions without requiring any modifications, which attests to the inherent fuel-flexibility of the technology. It was found that the modes of operation and flame stabilization of the SSC burner can be parametrized by the ratio of the speed of the mixture at the surface to its laminar burning velocity. The results affirm low emission operation is attainable on all fuels. In terms of nitrogen species other than oxides of nitrogen, the study found trace levels of N<sub>2</sub>O and NH<sub>3</sub> (< 0.1 ppm) emitted during steady state operation. However, the emission of those species can become significant during ignition and near the lean stability limit.

## 1. Introduction

Three common methods to stabilize premixed reactions are (1) aerodynamically, in either reverse, stagnant or divergent flows; (2) within a porous medium (inside the porous medium or at the outflow interface) [1]; and (3) on surface patterns. Generally, aerodynamically stabilized premixed reactions feature higher thermal intensity values (MW/m<sup>3</sup>-atm) when compared to surface-stabilized combustion (SSC) or combustion within porous media. This occurs because the bulk of the heat release in aerodynamically stabilized premixed reactions occurs

within a relatively thin flame zone. The actual thermal intensity depends on the physical size of the reaction zone, which varies with fuel composition, excess air, firing rate, and the pressure and temperature conditions of the reactants and flow field. Aerodynamically stabilized reactions like jet flames have narrow ranges of operation, often requiring multiple injectors to be staged in order to increase or reduce the firing rate. In many cases, jet flames require auxiliary piloting [2]. Several technology alternatives to widen the stability range of operation of aerodynamically stabilized premixed reactions are available. For example, swirl can be used to widen the reaction stability compared to

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the basic jet configuration, but this can lead to larger reaction zones which can increase NO<sub>x</sub> formation [3–11].

On the other hand, when the reactions are stabilized on a porous surface, they attach to the surface shape. As a result, at constant firing rate the combustion reactions of any gaseous fuel have a constant thermal intensity. One advantage of the extended surface is the stretching of the flame front or flame thinning. This increases heat losses in the burnout stage and reduces the residence time of the species in the high temperature zone, thus reducing NO<sub>x</sub> emissions [12]. In addition, at a fixed firing rate, the volume ratio of a surface stabilized reaction over the volume of an aerodynamically stabilized jet flame can be on the order of 50 fold. This characteristic gives the surface stabilized burner an advantage regarding the heat transfer from the combustion reactions to the surroundings and the load. The extended surface itself serves as a heat sink, cooling down the local reactions, yet re-radiating the heat to the thermal load. This local heat transfer rapidly cools the reactions, further contributing to the reduction of NO<sub>x</sub> formation rates. The local surface radiation also provides a stabilizing mechanism for the adjacent reaction, which therefore extends the lean stability limits and results in further reduction in NO<sub>x</sub> emissions, allowing low single digit NO<sub>x</sub> levels to be attained [13].

Besides low NO<sub>x</sub> benefits, this technology is also capable of burning low-calorific value (LCV) fuels and very lean fuel/air mixtures that would not normally be flammable for other combustion configurations, potentially allowing the exploitation of what would otherwise be wasted energy resources. The technology has been commonly applied for domestic boilers, radiating heaters, dryers, etc., [14–16]. Porous burners have also been tested for gas turbine applications [17]; Djordjevic et al., demonstrated that employing porous burners enhances the recirculation of heat to the fresh reactants, thus extending the combustor operational range [18].

The use of the conventional gaseous fossil fuels like liquefied petroleum gas (LPG) and natural gas (NG) in porous and surface stabilized combustion technology has been widely studied [14,16,19–29]. Moreover, the combustion of liquid fuels within the porous inert media of a radiant burner has also been examined. Results from experiments with liquid fuels indicate that the porous medium burner has advantages over conventional open spray flame burners for several reasons. These include enhanced evaporation of droplet spray owing to regenerative combustion characteristics, low emission of pollutants, high combustion intensity with moderate turndown ratio and compactness [30–32].

Yu et al., in 2013 compared the measured emissions (NO<sub>x</sub> and CO) and stability when burning NG of three types of porous-media burners: metal fiber (MF), ceramic (CM) and stainless steel fins (SF). The results indicate that the smaller the burner porosity was (porosity: SF < CM < MF), the higher the CO emission was and the lower the thermal efficiency was [23]. Keramotis and Founti studied the operation of a porous burner on biogas mixture comprised of 60% CH<sub>4</sub> and 40% CO<sub>2</sub> by volume [33]. Their results demonstrated wide stability limits of the technology with respect to thermal load and fire rate. The effect of CO<sub>2</sub> addition to NG mixtures is of particular importance since it is related to the increasing interest of using renewable bio-methane mixtures in practical applications. Hamamre et al., studied the combustion of LCV gases from anaerobic digestion of landfill wastes and those from waste pyrolysis [34]. Biomass gasification is another technique available to produce renewable gaseous fuels (synthetic gas or syngas) from the pyrolysis of solid fuels including biomass, coal, and other wastes. The syngas can be harnessed to produce heat and power with considerably lower NO<sub>x</sub> and suspended particle emissions, when compared to direct combustion of the solid fuel (used as a source) [35,36]. Song et al. studied the effect of firing rate for different LCV gases on temperature profiles, flame stability and CO emission. Their results show that the flame stability limits increased, while the CO emission decreased with an increase in the fuel calorific value [37]. Arrieta and Amell studied an equimolar blend of NG with syngas on a ceramic surface-stabilized combustion burner [38]. M. M. Abdelaal

et al., studied the effect of oxygen enrichment to the air on the combustion of a radiant porous burner [39]. Qiu and Hayden investigated oxygen-enriched combustion of NG in porous radiant burners. Their experimental results indicated an increase in the radiation output with an increase in oxygen concentrations in the combustion air [28].

The effect of H<sub>2</sub> addition to NG is relevant to the current interest in using renewable energy to produce H<sub>2</sub>. This concept, called power-to-gas (PtG), involves converting renewable electricity into hydrogen using electrolysis and using the natural gas grid for the storage and transport of energy stored in the form of hydrogen [40–42]. Another option involving renewable hydrogen is to store it in pressurized tanks, and when needed, reconverting it into electricity with fuel cells or hydrogen combustion engines. A recent review by Bailera et al. in 2017., includes a complete list of PtG projects worldwide [43].

Francisco et al., analyzed the combustion of hydrogen rich gaseous fuels using a porous burner in a confined environment [44]. The use of pure hydrogen or highly hydrogen-enriched methane was not considered in their research. Rørtveit et al., compared different low-NO<sub>x</sub> burners for combustion of methane and hydrogen mixtures including fiber burners, a swirl burner, and two porous, inert material burners with and without catalytic support [45]. For these experiments, the maximum volume fraction of hydrogen in the H<sub>2</sub>/CH<sub>4</sub> blend was 30%. Brockerhoff and Emost tested the performance of a premixed radiant burner for low NO<sub>x</sub> using NG/H<sub>2</sub> mixtures with up to 50% H<sub>2</sub> by volume [46]. In 2002, Tseng numerically investigated the effects of hydrogen addition (up to 60% by vol.) on methane combustion in a porous medium burner [47]. Alavandi and Agrawal studied combustion of hydrogen-syngas/methane fuel mixtures in a porous burner. They tested tri-fuel mixtures of CO + H<sub>2</sub> + NG including up to 50% H<sub>2</sub>. Natural gas was also tested as baseline fuel for comparison [48]. They found that, for a given adiabatic flame temperature, increasing H<sub>2</sub>/CO content in the fuel mixture decreased both the CO and NO<sub>x</sub> emissions. The presence of H<sub>2</sub>/CO in the fuel mixture also reduced the minimum temperature near the LBO limit, especially for higher percentages of CO and H<sub>2</sub> in the fuel.

Despite the numerous examples of studies examining the operation of porous or surface stabilized combustion devices on various fuels, it is evident that no systematic study has been carried out. Further, regarding the emissions performance of surface stabilized burners, NO<sub>x</sub> and CO are the primary species that have been studied. However, given the ability of this technology to stabilize very lean mixtures and operate with low local flame temperatures, it is conceivable that species such as N<sub>2</sub>O and NH<sub>3</sub> may have some chance to be emitted. The chemistry associated with these species indicates low temperatures can favor their formation [49]. The rising concentration of N<sub>2</sub>O in the atmosphere at rate of 0.26% yr<sup>-1</sup> (0.7 ppb yr<sup>-1</sup>) [50] indicates that nitrogen compounds are being introduced into the atmosphere at a rate greater than its rate of removal [51–52]. According to the Intergovernmental Panel on Climate Change (IPCC), the largest source of anthropogenic N<sub>2</sub>O is agriculture, driven mainly by the global use of over 80 million tons per year of nitrogen compounds as synthetic nitrogen fertilizers [50]. Similarly, the IPCC estimates that around 30% of the anthropogenic N<sub>2</sub>O is emitted as gaseous products from the combustion of fossil fuels and biomass (2 Tg N/year) with an upper limit of 3.7 Tg N/year and a lower limit of 0.7 Tg N/year, yet that high level of uncertainty warrants the need for reviewing the contribution of N<sub>2</sub>O from combustion sources. Similarly, ammonia (NH<sub>3</sub>) is also an important atmospheric pollutant species; recent studies have indicated that NH<sub>3</sub> emissions have been increasing over the last few decades on a global scale. This is a concern because NH<sub>3</sub> plays a significant role in the formation of atmospheric particulate matter, visibility degradation and atmospheric deposition of nitrogen to sensitive ecosystems [53]. Thus, the increase in NH<sub>3</sub> emissions negatively influences environmental and public health as well as climate change. For these reasons, it is important to have a clear understanding of the combustion sources that emit NH<sub>3</sub> into the atmosphere. By capitalizing on recent advances in measurement methods for

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