Experimental Thermal and Fluid Science 35 (2011) 570–580

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

# Ultra-low-emission steam boiler constituted of reciprocal flow porous burner

William M. Barcellos [a,*], Luis Carlos E.O. Souza [a], Alexei V. Saveliev [b], Lawrence A. Kennedy [c]

[a] Federal University of Ceara, Graduate Program in Mechanical Engineering, 60.455-760 Fortaleza, Ceara, Brazil
[b] North Carolina State University, Department of Mechanical and Aerospace Engineering, Raleigh, NC 27606, USA
[c] University of Illinois at Chicago, Department of Mechanical Engineering, Chicago, IL 60607, USA

ARTICLE INFO

*Article history:*
Received 24 August 2010
Received in revised form 11 November 2010
Accepted 18 November 2010
Available online 25 November 2010

*Keywords:*
Filtration combustion
Reciprocal flow burner
Ultra-low $NO_x$ and CO emissions

ABSTRACT

This experimental study examined a low-emission steam boiler in which the filtration combustion technology was employed. This new boiler concept is consisted of a reciprocal flow porous burner, in which a combustion wave propagates along the reactor length. The boiler's burner is filled up by an inert porous material, which leads to a stable burning of ultra-lean fuel/air mixtures, operating below flammability limits of conventional burners. In reciprocal filtration combustion, the reaction zone travels back and forth along the length of the burner, maintaining a typical trapezoidal temperature distribution favorable to the energy extraction. Embedding heat exchangers into the ends of the porous bed results in an alternative low-emission high-efficiency boiler. The heat re-circulation inside the porous matrix and the low degree of thermal non-equilibrium between the gas and the solid phases result in ultra-low levels of CO and $NO_x$. Over an equivalence ratio range from 0.20 to 1.0 and a gas flow velocity range from 0.2 to 0.6 m/s, burning the technical methane, the developed prototype has reached efficiencies superior to 90% and $NO_x$ and CO emission levels lower than 1.0 and 0.5 ppm, respectively.



## 1. Introduction

Porous media combustion, known as filtration combustion, has been employed in a wide range of engineering applications, e.g. from industrial processes to the oxidation of waste gases to reduce their negative impacts on the environment [15,20]. However, applications for water heating systems and thermoelectric power generation [10,17] suggest promising alternatives to exploit hydrocarbon fuels, resulting extremely low consumption and emissions.

A number of research projects have developed strategies to extract energy from filtration combustion [2–6,8,14,21], showing that the heat transfer process in the porous bed is highly efficient. The use of a high-conductivity high-specific heat solid phase exploits porous combustion in surface combustor–heaters, in which the porous matrix is capable of retaining the heat produced by the reaction and transferring it to a cooler body (e.g., heat exchanger). In an indirect way, this significantly enhances the efficiency of the heat extraction from the combustion zone.

The combustion of premixed air–fuel mixtures in porous media is an internally self-organized process of heat recuperation, which differs significantly from homogeneous flames. This difference can be attributed to two main factors: the large area of surface of the porous media results in efficient heat transfer between the gas and the solid; and the intense mixing of the gas flowing in the porous media increases effective diffusion and heat transfer in the gas phase [4,11,24].

Filtration combustion in boiler and heater burners significantly extends its flammability limits to the region of ultra-low heat content mixtures with an excellent stability that is impossible in conventional burners [7]. Strong interstitial heat transfer leads to low degrees of thermal non-equilibrium between the gas and solid phases, allowing the thermal wave to be coupled with the combustion wave. This is characterized as the low-velocity regime, as defined by Babkin [1]. Upstream wave propagation, countercurrent to the gas flow, or the downstream propagation depends on the equivalence ratio ($\Phi$) and the gas flow velocity ($v_{gf}$) employed in the reaction. It defines respectively the subadiabatic and superadiabatic operation regimes [2,9,16].

The technique of utilizing filtration combustion with gas reciprocating flow has favored the development of simple reactor designs that exploit a typical trapezoidal temperature profile centralized in the burner, operating in the superadiabatic regime for ultra-lean mixtures. Employing reciprocal flow filtration combustion, two reaction zones travel away from each other, towards the reactor ends, and this leads to an intense heat transfer in the vicinity of heat exchangers. These features result in low characteristic operation temperatures (less than 1600 K) that produce ultra-low nitrogen oxides ($NO_x$) and carbon monoxide (CO) emissions [5,6].

Then, this research work aims to report a concluding experimental investigation about a new porous burner boiler concept

* Corresponding author. Tel.: +55 85 3366 9641; fax: +55 85 3366 9640.
*E-mail address:* william@posmec.ufc.br (W.M. Barcellos).

0894-1777/$ - see front matter © 2010 Elsevier Inc. All rights reserved.
doi:10.1016/j.expthermflusci.2010.11.005