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Research Paper

Performance of two-region porous inert medium burners operating at low thermal powers

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HIGHLIGHTS

- Performance of PIM burners operating in the low thermal power range is studied.
- Temperature distributions history is used to define the stability limits diagram.
- Higher stability limits to that experienced at high powers are observed.
- The behavior of the PIM burner during transient operations is also investigated.
- NO_x-emissions of < 2 ppm and CO-emission levels of < 10 ppm are observed.

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ABSTRACT

Performance of two-region, square-shaped porous inert medium (PIM) burners operating at low thermal powers (densities) of 0.7–2.5 kW (48.61–173.6 kW/m^2) was investigated. The smaller-pore region was made of perforated Cordierite plate. Performance was examined for two larger-pore combustion region materials. They had similar dimensions and were made of Nickel-chromium-steel alloy wire mesh (> 95% porosity) and SiC foam (10 ppi & ∼87% porosity). The temperature distribution histories were recorded along the burner system for extensive excess air ratios including the unsteady flashback, stable and unsteady blow-off operations. They were lately utilized to determine the stability limits diagram. They were shifted toward the ultra-lean range in agreement with the published data of similar power densities and deviated from that experienced at moderate and high powers. Alternatively, they had a slight dependency on the combustion region characteristics, particularly, the blow-off limit. The flashback and blow-off stability limits had peak excess air ratios of 2.2 and 2.8, respectively, at a thermal power (density) of 1.5 kW (104.2 kW/m^2). The confined stable range between the two limits diminishes with power. For the investigated power range, a common operating excess air ratio range of 2.2–2.4 is recommended. Outstanding ultra-low NO_x-emissions (< 2 ppm) were obtained. CO-emission becomes visible at powers ≤1.5 kW.

1. Introduction

Recently, PIM combustion technology with its tremendous performance characteristics was introduced as one of the outstanding solutions avoiding the complicated drawbacks experienced with free-flame combustion. It is a smart concept that can be able to fulfill all the urgent requirements of modern combustion engineers and the current environmental policies and legislations. They may be summarized in the extremely high thermal efficiency, the low level of pollutant emissions species, the wide modular range of stable combustion, and the capability of burning ultra-lean combustible mixtures or fuels with low-calorific value [1]. It is successfully devoted in a diverse number of numerous practical applications in the heating and energy fields. Thus, the PIM combustion topic attracts many researchers from many points of view such as understanding the physics behind this technology, improving its performance, and extending its utilization to cover wider spectrum of applications.

The development of the PIM combustion technology stands behind the gain of two key features. The first is the excess enthalpy flame theory that was adapted and successfully applied by Takeno and Sato [1]. The theory describes the way of how the whole three mechanisms of heat transfer interact between the gas and solid phases. This results in the recirculation of some of the released thermal energy internally from the hot product gases in reaction zone back into the incoming cold

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reactant gases without their direct interfering contact. Basically, it is well-known that the effective preheating of the incoming reactants is an important key feature of improving the combustion process [2,3]. The advantages of applying the excess enthalpy flame principle in PIM combustion are comprehensively stated by many researches such as [4–6]. The most relevant advantages to the present work are the considerable increase of the burning speed, the imposed superadiabatic combustion condition throughout the entire reaction region which maintains self-sustaining combustion wave, the extending of lean flammability limit to very dilute mixture compositions, and the significant reduction in the emissions constituents in the product gases.

The second is the primary outcomes of the pioneering study by Babkin et al. [7] which specifies five possible regimes that may exist when the combustion wave propagates through PIM materials at ambient conditions and at elevated operating pressure. Among these regimes, only the low-velocity and the high-velocity regimes are the most suitable to describe the combustion wave propagation in PIM burner applications [8,9]. Moreover, their study identifies a limiting criterion for the existence of such propagation or its suppression or quenching. They proposed a modified form of the dimensionless Peclet number to determine the required condition for propagating the combustion wave through PIM materials. It is defined as ($Pe = S_L d_{P,eqv}/\alpha_m > 65$). Here, S_L is the laminar burning velocity, $d_{p,\ eqv}$ is the equivalent pore diameter of the PIM, and ($\alpha_m = c_{p,m}\rho_m/\lambda_m$) is the thermal diffusivity of the unburned reactant mixture ($c_{p,m}$ is the specific heat, ρ_m the density and λ_m is the thermal conductivity of the reactants mixture). The Peclet number can be defined as the ratio between the thermal energy released due to the burning process to the energy losses into the PIM solid material [7–9]. Conversely, the flame will cease to propagate or be quenched when $Pe < 65$. Thus, this criterion performs the corner stone for all combustion stabilization techniques within PIM burners [8–10].

For a given reactants composition, the equivalent pore diameter may be considered as the only selectable and crucial parameter controlling the Peclet number criterion. Other parameters are obviously function of the initial and operating conditions [7,11]. Based on the extensive arguments made in [8,9], there is a critical equivalent pore size. Above this value, the combustion wave propagates in the high-velocity regime which is called the supercritical combustion mode ($Pe > 65$). Otherwise, the combustion wave is entirely quenched or propagates in the low-velocity regime which is called the subcritical combustion mode ($Pe < 65$).

The supercritical combustion mode is characterized by high flame speeds in the range of 0.1 to 10 m/s which exceed the corresponding laminar flame speeds by the order of 10–30 times [9,12]. Therefore, a rapid countercurrent combustion wave to the incoming reactants is intrinsically created in this mode.

Conversely, when the combustion wave proceeds in the subcritical combustion mode, it behaves in totally different way [8,9,13–16]. It is called also the filtration combustion. In this mode, the incoming reactants flow velocity, which is called the filtration velocity, appears as an additional operating parameter that significantly influences the features of combustion [9,16], besides the properties of both the PIM material and the reactants mixture. To initiate and constitute combustion wave propagation in this mode, some preheating to the PIM material [13,17] and imposing a flow velocity (≈ 0.4 m/s [9]) should be provided. Otherwise, it will be quenched [9,12]. The wave propagation in this regime is dominated by the interfacial heat transfer between the PIM solid material and the reactant gases through the strong interphase thermal energy exchange by the three modes of heat transfer. Depending on the filtration velocity value, three modes of combustion wave propagation may be performed. As discussed in details by [8,9], they are called the subadiabatic, standing wave and superadiabatic. Increasing or decreasing the filtration velocity will determine in which mode the combustion process will be carried out and, in turn, in which direction the wave will travel. In subadiabatic mode the wave will travel in countercurrent to the filtration velocity, while the inverse in the superadiabatic mode. Both are characterized by very slow velocity 10^{-5}–10^{-4} m/s [1,8,9,13–17]. Thus, combustion process within PIM material has an intrinsic tendency to travel in some proper direction which depends on the PIM characteristics and the initial and operating parameters. To obtain a self-sustaining stable combustion process over varying wide ranges of initial and operating conditions, a particular action should be dedicated.

In reality, obtaining stable combustion is the primary objective of any combustion system. Hence, it can be considered as the major performance parameter in developing PIM burners and in determining their validity for a certain particular application. Also, such stability performance influences all other performance parameters such as the temperature field distributions, flame front structure, stability limits, combustion efficiency, intermolecular species formation and their distributions, and emissions particulates in product gases. Trimis and Wawrzinek [8] summarized all the current proposed techniques for stabilizing the combustion in PIM burners.

Among all of these stabilization techniques, the two-region approach, which is firstly adapted by Trimis and Durst [18], is the most appropriate for many useful atmospheric applications [19]. This is because its tremendous advantages over other proposed flame stabilization approaches such as the simple and durable construction, the ease startup and extinction processes, the flexible operation and control over wide modular power and mixture composition ranges of stable combustion, and the simple integration with other energy conversion systems. The two-region technique consists of two PIM materials with different equivalent pore sizes in firm contact at their interface. The equivalent pore size of the upstream region, which is called the quenching region, should be selected as smaller than the critical value to satisfy the subcritical combustion mode ($Pe < 65$). The equivalent pore size of the downstream region, which is called the combustion zone, should be selected as larger than the critical value to operate in the supercritical combustion mode ($Pe > 65$). Thus, the combustion wave after ignition propagates in the high-velocity regime in the upstream direction to settle at the end, i.e. stabilized, in the interface region between the two regions. This action can continue over a wide range of the reactants mixture compositions and powers. The effective thermal properties of this region in the upstream direction must be excellent to overcome the opposite convective cooling effects for highly diluted mixture compositions. This will extend the stable operation into highly-lean values before reaching the unstable blow-off situation.

Beside its basic function in impeding the combustion wave to propagate in the upstream direction, the smaller-pore region is preheated due to the received conduction and back radiation heat transfer from the adjacent high-temperature combustion region. This results in an effective preheating to the incoming reactants gases due to the interfacial convective heat transfer mechanism in an efficient, internal heat recuperation process. Therefore, this region may be also called the preheating region [8]. Based on the preceding discussion, there are three possible ways in which the smaller-pore region may behave. It works in the superadiabatic combustion mode when the combustion wave will be expelled toward the interface plane between the two regions and stabilizes there. Or it works in the stationary combustion mode where the combustion wave will be confined within it at an appropriate location. This can be done over a limited range of powers and compositions. Finally, it works in the subadiabatic combustion mode when the combustion wave accompanying with a thermal wave continues their crawling in the upstream direction. This will lead to the constitution of the flashback condition at the end when the temperature of the upstream face of this region reaches the spontaneous ignition temperature. For a given burner configuration, this will occur for every power value in the operating range at a specific lower-lean mixture composition. In reality, the performance of this technique was extensively subjected to experimental and numerical studies [4–6,10,18–35].

However, most of these studies are restricted to stable moderate and