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Experiment on superadiabatic radiant burner with augmented preheating

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HIGHLIGHTS

- Potential of superadiabatic radiant burners (SRBs) is experimentally confirmed.
- The SRB consists of two-layered porous media, a preheater and radiation rods.
- The SRB can be operated at very fuel-lean condition due to enhanced heat recovery.
- CO/NO_x emissions are reduced compared with the conventional porous radiant burners.
- The SRB is acceptable for practical applications.

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ABSTRACT

A radiant porous burner with augmented preheating (i.e., superadiabatic radiant burner, SRB) is experimentally investigated. The porous alumina (Al_2O_3) burner with a square cross-section consists of a small-pored upstream section for internally preheating the incoming gas mixture, a large-pored downstream section for establishing flame, a preheater for externally recovering heat from the exiting flue gas and preheating the inlet air for the burner in addition to the internal heat recirculation in the small-pored upstream section, and radiation corridors for extracting heat from the flame and transferring it to radiating disk surfaces. Temperature distribution and combustion stability limits of flame in the SRB and the nitrogen oxide (NO_x) and carbon monoxide (CO) emissions are measured. Results show that the SRB can be operated even at very fuel-lean condition because of the internal and external heat recirculation, showing blow-off and flash-back limits for a given fuel-equivalence ratio. It is observed that the superadiabatic radiation temperature on the disk surfaces is higher than the flue gas temperature at the same axial location, experimentally confirming the previous theoretical and computational results of SRBs. Improved performance of CO and NO_x emissions compared with the conventional porous radiant burners also indicates that the SRB is acceptable for practical application.

1. Introduction

In response to the current concerns over climate change and energy security, there has been substantial interest in either developing high-efficiency, low-emission combustion devices or finding alternative energy sources. Porous burners have been considered as one possible technology for achieving the high-efficiency and low-emission since they can recirculate heat from the burned hot downstream gas to the unburned, incoming cold gas through the porous medium and thus operate under very fuel-lean condition [1,2]. In addition, it is known that the porous burners have the fuel flexibility, implying that alternative and renewable fuels such as low-calorific syngas from waste pyrolysis and landfill gas can be utilized [3].

Recently a novel radiant porous burner with augmented preheating (i.e., superadiabatic radiant burner, SRB) was suggested and computationally investigated [4]. The SRB consists of a small-pored upstream section for internally preheating the incoming gas mixture, a large-pored downstream section for establishing flame, a preheater for externally recovering heat from the exiting

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flue gas and preheating the inlet air for the burner in addition to the internal heat recirculation in the small-pored upstream section, and radiation corridors for extracting heat from the flame and transferring it to radiating disk surfaces. The two-section porous burners have been studied by various researchers, since the small-pored upstream section can play a role as a flashback arrestor as well as the internal preheater, and the interface between the two sections can stabilize the flame over a wide range of flow rates [5–11]. It was shown that for fuel-lean conditions the external heat recirculation due to the preheater in addition to the internal heat recirculation in the small-pored section can increase the local flame temperature in the SRB beyond the adiabatic flame temperature. Also, extracting and conducting heat from the superadiabatic flame through the embedded radiation corridors (rods), each of which is composed of a finned stem and a radiation disk at the downstream end with high thermal conductivity, the heat is radiated to the target at a higher temperature than the flue gas. Efficiencies of the superadiabatic radiant burner were found to be remarkably enhanced compared with the conventional porous burners.

The concept of external heat recirculation by installing a preheater in a porous burner has not been extensively investigated, though some fundamental studies were reported [12]. Meanwhile, the incorporation of the superadiabatic burners into thermophotovoltaic (TPV) systems in which the direct generation of electricity through thermal radiation is possible can be suggested since the radiation disk surfaces at the downstream end of the radiation corridors are appropriate to effectively radiate heat into photovoltaic cells. Actually the concept of using porous burners instead of conventional cylindrical combustors in the TPV systems has been suggested [13], but the radiation of the heat that is generated from flame into the photovoltaic cells without the radiation corridors is not effective since the flame is submerged in the porous medium. Thus, the SRBs seem to have a significant improvement in the performance compared with the conventional porous burners, particularly for the specific applications such as TPV systems that require effective radiation to the target. Considering that the concept of the SRB has been suggested via a computational investigation, it is needed to experimentally demonstrate it.

In view of the above considerations, in this study we aim to experimentally demonstrate the novel concept of the SRB, with the following specific objectives. The first objective is to design and fabricate a laboratory scale SRB for demonstrating the concept. The second objective is to measure the combustion stability limits of fuel-lean propane (C_3H_8)/air flames in the SRB at normal temperature and pressure (NTP), including the blow-off (i.e., high-stretch extinction) limits and the flashback (i.e., low-stretch) limits, in order to provide the fundamental database of steady-state operating limits of the SRB. The third objective is to confirm the superadiabatic effects of the SRB. We measure the temperature distribution in the porous medium to observe if the peak flame temperature is higher than the adiabatic flame temperature of the corresponding fuel/air mixture. Temperatures of radiating disk surfaces and the flue gas at the same axial location are also measured to observe if the former is higher than the latter. The fourth objective is to measure the nitrogen oxide (NO_x) and carbon monoxide (CO) emissions of the premixed C_3H_8/air flames in the SRB in order to observe if the SRB can exhibit NO_x and CO reduction. Finally, we estimate the thermal efficiencies of the SRB.

The configuration of the designed SRB, the combustion stability limits and temperature distribution of the premixed C_3H_8/air flames in the SRB, the superadiabatic effects of the SRB and the CO and NO_x emissions and efficiencies of the SRB will be subsequently presented, following the descriptions of the experimental methods used during this investigation.

2. Experimental methods

The superadiabatic radiant burner with two porous sections (i.e., two-layer porous media), radiation rods embedded in the porous media and a preheater is considered for the present investigation since it is expected to experimentally demonstrate the superadiabatic effects. A diagram of the experimental apparatus used in this study is shown in Fig. 1. It consists of a test SRB, a fuel–air mixture supply system, a ventilation system, thermocouples for measuring temperature distribution in the SRB, a gas analyzer for measuring NO_x and CO emissions and a digital camera (Sony A65) for recording flame and radiation images.

Air (21% oxygen (O_2)/79% nitrogen (N_2) in volume, purity >99.9%) and C_3H_8 (purity >99.9999%) are supplied respectively to a preheater and to a mixing chamber using commercial mass flow controllers (Aera: 0–5 slm and MKS: 0–200 slm) with accuracy ±1.0% of full scale. The mass flow controllers are calibrated using a bubble meter. Air is preheated through the preheater and then it is delivered to the mixing chamber. The preheater is a spiral fin tube with the inner diameter of 10.2 mm (stainless steel, SUS316L) and is located between the downstream end of the porous medium of the SRB and the radiation disks of the radiation rods. Thus, heat in exhaust gas is recovered to preheat fresh air in the preheater. The preheated air and fuel are mixed in the mixing chamber and are issued from the bottom of a distributor ($68 \times 68 \times 60\ mm^3$) that is filled with stainless steel beads with an average bead diameter of 1.5 mm for obtaining uniform flow. The distributor is windowed to detect flashback using quartz. The preheated air–fuel mixture is fed into the porous medium of the SRB with uniform flow.

The test SRB is two-layered: a porous medium with fine alumina (Al_2O_3) foam (PM1: 60 ppi (pores per inch), $68.0 \times 68.0 \times 40.0\ mm^3$, Drache Inc.) upstream and the other porous medium with coarse Al_2O_3 foam (PM2: 20 ppi, $68.0 \times 68.0 \times 40.0\ mm^3$, Drache Inc.) downstream. The sides of porous media are surrounded by the heat-insulated case with thickness of 5.0 mm (SUS316L, $78 \times 78 \times 140\ mm^3$). The preheated air–fuel mixture is ignited at the exhaust outlet of the burner by a torch-igniter. Once the mixture is ignited, the flame moves backward and is stabilized in the PM2 or on the interface between the PM1 and PM2. Heat from the flame is extracted through the fins around the stem of the embedded radiation rods (silicon carbide, SiC), conducted through the stem and radiated at the radiation disk surface. Figs. 2 and 3 show the photographs of the assembled and disassembled SRB and the typical images of the radiating PM2 and disks, respectively.

R-type thermocouples with a bead diameter of 250 ± 20 μm and an accuracy of ± 0.25% are used to measure the temperature (T) distribution in the PM2. A stage on which the thermocouples are fixed can move through a hole that is drilled along the axial centerline, identifying the maximum flame temperature and its location. The preheated air temperature is measured using K-type thermocouples with a bead diameter of 250 ± 20 μm and an accuracy of ±0.75%. K-type thermocouples are also used to measure the radiation disk surface temperature and the exhaust gas temperature at the same axial location as the disk surface. The disk surface temperature and the exhaust gas temperature are obtained by averaging measurements at the same axial location but different points.

The combustion stability limits of fuel-lean C_3H_8/air flames in the SRB are measured by varying the fuel-equivalence ratio ϕ and the burner inlet velocity V that is defined as the total volume flow rate of the mixture divided by the cross-sectional area of the PM1. Propane has been chosen as fuel since it can be used in practical applications. Once a flame is stabilized in the PM2 as aforementioned, ϕ is set to a fixed value and then V is varied to find the combustion stability limits. Given ϕ two combustion stability