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Multiscale thermal nonequilibria for record superadiabatic-radiant-burner efficiency: Experiment and analyses

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ABSTRACT

A record radiation efficiency of 37% is achieved using a two-layered porous (SiC foam, fine and course) burner using multiscale thermal nonequilibria and effective heat recirculation. The porous burner holds the flame and heats finned SiC rods effectively conducting heat to radiating disks downstream, while the flue gas is intercepted before leaving the disk spacing by a preheater carrying secondary air that mixes upstream with the fuel and primary air. These result in superadiabatic combustion in porous layers and fuel-gas preheating that causes exiting flue gas having a temperature lower than the radiating disks. These orchestrated heat recirculation and preheating extend the lean flammability to 0.24 equivalence ratio, and allow the flue gas temperature to be over 50 K below the radiating disks temperature. A three-dimensional model of the structures with a two-step combustion reaction allow to predict the combustion and emission and related convection, conduction and radiation heat transfer, with excellent agreement with the experiments over wide ranges of fuel flow rate and equivalence ratio.

1. Introduction

The premixed combustion in porous media often becomes a superadiabatic combustion which is also known as “excess enthalpy” burning caused by an internal heat recirculation [1–12]. The well-known internal heat recirculation in the porous burner consists of interstitial convection, solid conduction, and surface radiation of combustion heat to internally preheat the incoming fuel–air mixture flow. Due to this heat recirculation, the porous burners are capable of burning low-calorific-value fuels (low fuel equivalence ratios) that would not normally be combustible, allowing for the utilization of what would otherwise be wasted energy resources [13]. The internal heat recirculation also makes it possible for the porous burner to operate at higher flame speeds (large energy throughputs) than the laminar flame, greatly reducing emissions and extending combustion stability which is characterized by flame blow-off, flashback or extinction [3,13–15]. In addition to the internal heat recirculation, the heat recovery from exiting exhaust gas using a preheater can further lower the fuel lean limit to as low as 0.1 equivalence ratio with a mixture of methane and hydrogen [10,14,16]. Such an ultra-lean combustion occurring at low temperatures emits less NO_x, unburned hydrocarbon (UHC) and CO [8].

The early design of the porous burners used a single-layered (monolithic) burner made of ceramic foam materials [1,14,17] which was often used to study a non-stationary combustion (filtration combustion). In recent years, multi-layer porous burners have been extensively investigated [2,8,9,16,18,19] due to the unique advantages, e.g., submerged flame, extended flammability limit, lean combustion and low emission. A two-layered porous burner first used by Durst and Trimis [20] can stabilize flame at the interface between the two different porous layers with different distinctive geometrical properties (porosity and pore diameter) over a wide range of flow rate.

In the two-layered porous burner, the first layer (upstream) of the burner has finer (smaller) pores than that of the second layer (downstream). The pore diameter of the finer layer is typically in the order of 500 μm and less than the minimum diameter required for the flame propagation to serve as a flame arrestor, whereas the pore diameter of the coarse layer is about 2 mm with a similar porosity to that of the finer layer [8]. The flame stabilization (blow-off, flashback or extinction) near the interface is greatly affected by the rapid changes in gas velocity and heat recirculation across the interface of the porous layers [13,15].

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Nomenclature

A	pre-exponential factor of combustion reaction [1/s]
c_p	specific heat [J/kg-K]
C_j	molar concentration of species j [kmol/m^3]
D_p	pore diameter [m]
E_a	activation energy [J/kmol]
h_{gs}	interstitial heat transfer coefficient [W/m^2-K]
k	thermal conductivity [W/m-K]
k_r	rate constant
L	length [m]
M_w	molecular weight [kg/kmol]
$\mathrm{Nu}_{D,p}$	Nusselt number
N_R	number of reactions
P	pressure [Pa]
Q	heat rate [W]
R	reaction rate [kg/m^3-s]
Re	Reynolds number, $\rho_g \varepsilon u_g D_p/\mu$
R_g	universal gas constant [J/kmol-K]
$\dot{S}_{r,c}$	rate of heat generation [W/m^3]
T	temperature [K]
u	velocity [m/s]
x	coordinate [m]

Greek letters

β	temperature exponent
ΔH_r	heat of reaction [W/kg]
ε	porosity
ε_r	emissivity
η	exponent
η_r	radiation efficiency
μ	dynamic viscosity [Pa-s]
υ	stoichiometric coefficient
ρ	density [kg/m^3]
σ_e	extinction coefficient [1/m]
σ_{SB}	Stefan-Boltzmann constant [W/m^2-K^4]
ϕ	equivalence ratio

Subscripts

1,2	indices
a	activation
amb	ambient
exh	exhaust
F	fuel or flame
g	gas phase
gs	gas to solid
i, j	index
k	conduction
p	pore or particle
ph	preheater
r	radiation or reaction
s	solid phase
sr	radiating surface
stoich	stoichiometric
t	target
u	advection

Superscripts

m	exponent or coefficient

The modeling of the lean premixed combustion in porous media employs a local volume-averaged formulation [5,10,29] and direct simulation [4] based on either thermal equilibrium or using nonequilibrium treatment. The interstitial heat transfer inside the small-scale pores of the porous media plays a significant role in heat recirculation in porous burners [5,8,21]. The volume-averaged model could not predict the minimum sustainable flame speeds in the burner (flashback limit) and the model predictions of flame speed increasingly deviated from experimental results as the equivalence ratio approached stoichiometric because no turbulence or flame-stretching effects in the small-scale porous structures were considered [22].

Despite the notable progress in the field of porous burners, as presented in a detailed review on the various designs of porous burners by Wood and Harris [13], the combustion of lean mixtures of fuel and air, remains relatively unexplored. One of the main topics that have not been fully explored is the effect of the use of supplementary external preheating of the incoming fuel/air mixture [13]. Here, a two-layered SiC porous burner with an external preheater and a radiation corridor, as shown in Fig. 1, was experimentally and numerically investigated for lean superadiabatic combustion of propane/air mixtures. The effects of the operating parameters for the porous burner such as fuel flow rate and equivalence ratio on the combustion characteristics and radiation efficiencies are discussed and the experimental and numerical results are compared.

2. Methods

2.1. Experiments

The superadiabatic radiant burner (SRB) 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 provide superadiabatic flame temperature. A diagram of the experimental apparatus used in this study is shown in Fig. 2. The dimensions of the SRB are given in Table 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 nitrogen oxide (NO_x) and carbon monoxide (CO) emissions and a digital camera (Sony A65) for recording flame and radiation images.

Air (21% O_2/79% 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 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 silicon carbide (SiC) foam (PM1: 65 ppi, $68 \times 68 \times 40$ mm^3, Ultramet Inc.) upstream and the other porous medium with coarse SiC foam (PM2: 20 ppi, $68 \times 68 \times 40$ mm^3, Ultramet Inc.) downstream. The sides of porous media are surrounded by the heat-insulated case with thickness of 5 mm (SUS316L, $78 \times 78 \times 140$ mm^3). The preheated air–fuel mixture is ignited at the exhaust outlet of the