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Experimental and theoretical study of excess enthalpy flames stabilized in a radial multi-channel as a model cylindrical porous medium burner

Dae Keun Lee*, Dong-Soon Noh

Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon, Republic of Korea

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ABSTRACT

An experimental and theoretical study was conducted on excess enthalpy flames stabilized in a radial multi-channel as a model cylindrical radial-flow porous medium burner. In experiments, the flame position and burning velocity were directly measured under various mixture conditions. The result showed that the multi-channel flames had excess burning velocities due to heat recirculation via the channel walls. As the flow rate reduced, its radial position decreased with a linear-to-nonlinear transition and it was extinguished at its minimum radial position. To elucidate the mechanisms behind these behaviors, a theoretical analysis was conducted. From the rotational symmetry, the multi-channel was simplified to a slightly-diverging adiabatic channel. After assuming a one-dimensional far-field stabilized flame, the entire region was divided into the classical flame zone and outer regions and then asymptotic solutions were obtained. The result indicated the existence of a turning-point flame behavior with two different branches, one of which qualitatively agreed with our experimental results. Detailed examination showed that there are three different stabilization mechanisms, i.e., the flow divergence, the heat recirculation and an enhanced heat diffusion. The heat recirculation is a long-range gas–solid interaction leading to the excess-enthalpy burning, whereas the enhanced heat diffusion is a short-range flame-solid interaction dispersing heat from the flame zone to the neighboring regions and so suppressing the excessive burning. The competition between these two is believed to cause the transition behavior of flames prior to extinction in our multi-channel and further in cylindrical porous media.

1. Introduction

Submerged combustion of fuel-oxidant mixture in a porous medium (PM) [1] has been known as the most simple method of obtaining excess enthalpy flames [2,3] without use of any external device. Just by inserting a heat-conductive porous solid into the flame zone, exhaust heat is recirculated to the fresh mixture due to interphase heat transfer and conductive and radiative heat transfers of the solid around the flame. This additional mixture preheating makes the submerged flame have an excess enthalpy above the adiabatic flame temperature. In wide practical applications PM burners have been used for maximizing the amount of fuel burning in a given combustion volume, extending the flammability limits, enhancing radiation emission or increasing system efficiency [4,5].

During the past several decades, much experimental [6–8] and theoretical [9–15] researches have been devoted to understanding the characteristics of flame stabilization affected not only by mixture conditions but also by solid properties. Since the excess-enthalpy burning in PM is the result of gas-solid thermal interaction, a reaction–diffusion wave in gas should be accompanied by a heat diffusion wave in solid. So the wave propagation speed relative to the solid is generally less than several mm/min due to large solid heat capacity [16]. In addition, small pores in PM reduce degrees-of-freedom of the burner-scale flame dynamics. On the other hand, the flame temperature rise, as well as its enlarged surface area due to its pore-scale curvature, results in an average burning velocity several times larger than the adiabatic value of the mixture. Moreover, the burning velocity is not a mixture-intrinsic property, so the propagation speed is not linear with respect to the mixture velocity. Therefore, stationary flames in homogeneous PMs with uniform filtration have been rarely reported [8,14,15]. Flames have been usually stabilized around nonhomogeneous positions, for example, just behind a PM inlet [6,10], at an interface between two different PMs [7,17,18], or in a thermally nonhomogeneous PM [7,19].

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* Corresponding author.
E-mail address: dklee@kier.re.kr (D.K. Lee).

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Nomenclature

A	Pre-exponential factor of Arrhenius reaction
C_p	Specific heat of mixture
D	Mass diffusivity of a deficient reactant
d	Flame thickness, $d = k/\rho C_p U_b$
Da	Damköhler number defined in (2)
h	Convective heat transfer coefficient
K	Solid thermal conductance parameter, $K = k_s w/kl$
k	Thermal conductivity
k_δ	Solid thermal conductance parameter, $k_\delta = k_s w/k\delta$
l	Arc length
Le	Lewis number
N	Convective heat transfer parameter, $N = \mathrm{Nu}(d/l)^2$
n	Convective heat transfer parameter defined in (5)
Nu	Nusselt number
Q_r	Heat recirculation defined in (39)
R_f	Flame position in the radial multi-channel
r	Dimensionless radial distance from the channel origin (Fig. 6)
T, T_0	Gas temperature and its inlet value
T_s	Solid temperature
U_{ad}	Laminar burning velocity
U_b	Burning velocity in the radial multi-channel or diverging channel
u	Local mixture velocity
V_c, $\tilde{V}_c$	Dimensional and dimensionless mixture flow rates per unit depth of a channel
V_t	Total mixture flow rate of the radial multi-channel
W	Channel width
w	Wall thickness
X	Dimensionless outer-region coordinate
Y, Y_0	Mass fraction of a deficient reactant and inlet mass fraction
y	Dimensionless mass fraction

Greeks

α	Diverging angle
β	Activation energy parameter
δ	Adiabatic flame thickness, $\delta = k/\rho C_p U_{ad}$
κ	Solid heat conductance parameter defined in (5)
λ	Solution of the characteristic equation, defined in (13)
ϕ	Equivalence ratio
ψ, Ψ	Dimensionless solid temperature
ρ	Gas density
θ, Θ	Dimensionless gas temperature
ξ	Dimensionless flame-attached coordinate of $O(d)$
ξ_r	Dimensionless position of temperature reversal (Fig. 7)
ζ	Dimensionless reaction-zone coordinate

Subscripts and superscripts

f	Quantity at the flame position
$\pm$	Post- and pre-flame zones, respectively
$\hat{}$	Quantity in the reaction zone

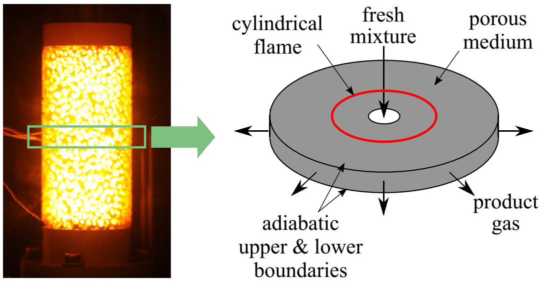

Fig. 1. An example of a cylindrical radial-flow porous medium burner.

Diverging mixture flow, although less of a concern, can provide a different kind of flame stabilization, even in a homogeneous PM [5,20–26]. When the mixture velocity is retarded along the flow direction, at least one stationary position may exist in PM. Kakutkina and Babkin [20] experimentally showed that a flame has its stationary position in a spherically divergent flow in PM without respect to ignition locations. Their theoretical model predicted a linear-to-nonlinear transition of the flame radius as the flow rate decreases. Zhdanok et al. [21] theoretically showed that, if a cylindrical or spherical PM is radially finite, two different flames of a given mixture can be stabilized in upstream and downstream of the PM. Dobrego et al. [22] discussed a limiting radius of a cylindrical flame in a disk-shaped PM. Futko et al. [23] predicted a nonlinear change of flame radius in a disk-sector-type PM. Mohamad [24] numerically showed a linear change of flame radius with mixture flow rate in a cylindrical PM. For cylindrical two-section PMs, Drobyshevich [25] numerically predicted a five-fold increase in burning rate of interface-stabilized flames, in comparison with a one-body PM. Bedoya et al. [26] conducted comprehensive numerical studies on flame temperature and burning velocity affected by flow patterns in PMs. Most of these research works were focused on the effects of flow divergence or heat loss on the flame stabilization, but other effects stemming from the heat recirculation or the flame structure deformation by the gas–solid interaction have not been surveyed in detail.

Recently, the authors have been conducting research on practical applications of cylindrical PM burners as efficient radiation emitters and non-catalytic partial oxidation fuel reformers. As shown in Fig. 1, fresh mixture was axially fed through a concentric hole in the PM made of silicon carbide foam, and then radiated outward. Once a stable submerged flame was established, the PM emitted uniform radiation. However, unfavorable phenomena, such as its flashback, blowout and sudden extinction, were also observed, depending on mixture conditions. Since random pores of the cylindrical PM did not permit any visual and intrusive measurements of the submerged flames, detailed flame behaviors could not be identified. Probably for the same reason, the former theoretical and numerical results [5,20–26] could not be confirmed by sufficient experimental measurements. This study was motivated by these difficulties.

Objectives of the present study are to find the flame stabilization characteristics in cylindrical radial-flow PMs and to elucidate the mechanisms behind the characteristic flame behaviors. To this end, we conducted experiments, detailed in Section 2, where a disk-shaped part of the cylindrical sponge-like PM in Fig. 1 was modeled as a radial multi-channel made of thin quartz plates (see Fig. 2). Contrary to a macroscopically uniform pore structure of the sponge-like PM, our model PM has a linearly increasing channel width for gas flow. However, an analogy of the channel walls to solid skeletons of the PM in the heat recirculation mechanism produced excess enthalpy flames. The flame behaviors in this well-defined model PM were then analyzed theoretically, as detailed in Section 3. From its rotational symmetry, the problem was spontaneously simplified to that of a single diverging channel. After considering the characteristic length scales in both phases and dividing the entire region into the classical flame zone and an additional outer region, the flame structure was analyzed by the activation energy asymptotics and the method of matched asymptotic expansions. As results, mathematical expressions