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Experimental and numerical studies on the flame instabilities in porous media

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HIGHLIGHTS

- ▶ Study the effect of the equivalence ratio on the flame breakup and inclination experimentally.
- ▶ Detailed analysis of the flue gas emission.
- ▶ Detailed analysis of the inclinational flame evolution with an initial inclinational angle.
- ▶ Simulate the dynamics of the inclinational flame without an initial inclinational angle.

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ABSTRACT

Flame instabilities of inclination and breakup for lean CH_4/air combustion in porous media are studied experimentally and numerically. Inclination and breakup are observed in the quartz tube filled with alumina pellets of 3 mm in diameter for equivalence ratio range of 0.435–0.490. The effect of the equivalence ratio on the flame inclination and breakup are discussed and the results show that the equivalence ratio plays an important role on the breakup and flame inclination. Breakups always happen when the inclinational angle reaches 54–60°. In order to explain the motivities of the inclination, a two-dimensional one-step chemical reaction, two-temperature model without initial angles are carried out to simulate the experimental cases. In order to check the possible motivities of inclination, we assumed profiles (not uniform) of inlet velocity of premixed gas and equivalence ratio at inlet, different porosities in the tube, half the same on the right, half on the left, in the simulations. The results show that the inhomogeneous inlet velocity gives slight influence on the inclination, but the different distribution of porosity and the inhomogeneous equivalence ratio at inlet give great influences on the inclination. Calculation results show that the heat loss have a significant influence in determining the flame shape at the initial moment and lead to an increase in the development of the inclination instability. At a low mixture velocity, hydrodynamic effect on the inclination instability is ignored, while the inclination angle of the flame front continually increases as the mixture velocity increase.

1. Introduction

Combustion of premixed gases in porous media has received considerable attentions due to its advantages such as high combustion efficiency, low lean combustible limits and low emissions in comparison with the combustion in free space [1–4]. A number of studies on the combustion in porous media have been extensively executed during the last decade [5–8]. Some significant developments on the studies of the flame characteristics in porous media, such as the gas and solid temperatures, the combustion wave propagation, the pollution emission, and the heat transfer mechanism have been obtained [9–13].

However, the combustion in porous media may become unstable and some flame instability phenomena were observed in experimental studies [14,15]. The flame instability phenomena include the inclination which is the most common one, breakup and hot sport, etc. A great progress had been made on the flame inclination due to experimental [14,15], numerical [16–19] and analytical [20,21] studies.

Minaev et al. [22] investigated the combustion wave instability in the filtration combustion experimentally. A 500-mm-long quartz tube with a diameter of 40 mm was used as combustor, which was filled with grained carborundum. Inclinational flame fronts were observed for different equivalence ratios and inlet mixtures velocities. In the theoretical study of Dobrego et al. [23], dynamics of filtration combustion front perturbation was presented and their conformity to the theoretical model was revealed.

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Nomenclature

C_g	specific heat of gas (J/(kg K))
d	pellet diameter (mm)
G_{er}	difference of equivalence ratio
h_{air}	convective heat transfer coefficient between burner wall and the ambient (W/m^2 K)
p	pressure (Pa)
T_{ex}	temperature of outer wall (K)
T_{in}	temperature of inner wall (K)
w_i	chemical reaction rate of species i (kmol/m^3 s)
Y	mass fraction
Greek symbols	
ε	porosity
ε_r	emissivity of solid surface of pellets
λ_{eff-g}	effective thermal conductivity of gas (W/m K)
λ_{rad}	radiative heat transfer coefficient (W/m^2 K)
ρ_g	density of gas (kg/m^3)
C_s	specific heat of solid (J/(kg K))
D_d	thermal diffusivity (m^2/s)
G_p	difference of porosity
h_v	volumetric convective heat transfer coefficient (W/m^3 K)
T_{air}	ambient temperature (K)
T_g	gas temperature (K)
$u_{g,av}$	average velocity of gas at inlet (m/s)
W_i	molecular weight of species i
ϕ_{av}	average equivalance ratio
ε_{s1}	emissivity of tube surface
λ_{eff-s}	effective thermal conductivity of solid (W/m K)
λ_{s1}	thermal conductivity of tube (W/m K)
ρ_s	density of solid (kg/m^3)

The analytical and experimental results showed that the inclination amplitude of flame ΔX is proportional to the combustion wave speed u_w and combustor diameter D, but inversely proportional to the pellet diameter d: $\Delta X \approx 0.04u_w(D/d)$. The maximum inclination amplitude could be expressed as: $\Delta X_{\max} \approx 0.5u_w(u_0/(1-u_0))(D^2/d)$, where u_0 is the dimensionless wave velocity. 2-D numerical simulations were performed to validate the expressions of inclination amplitude.

In the experimental study of Dobrego et al. [24], the flame instabilities of inclination and breakup in the porous media were observed. In some cases, flame inclination reached its saturation and it would not grow again. In other cases, the inclination grew in approximately a linear way until its front broke. Kim et al. [25] investigated the combustion characteristics of a lean methane–air mixture in a heated porous sand bed both experimentally and numerically. S-shaped flame behavior was found and the author categorized the S-shaped behavior into three regimes, namely high, moderate and low velocity regimes. For the moderate velocity regime, a stable flat flame was viewed while in the high velocity regime, oscillatory behavior was viewed. The flame behavior in the low velocity regime was similar to that in the flameless combustion mode. Zheng et al. [26] studied the evolution of the flame inclination in porous media numerically. Inclination flame fronts were confirmed during the combustion wave propagation with an initial inclinational angle, the mechanism of inclinational instability of premixed combustion was analyzed. The study showed that, the increases of solid conductivity, pellet diameter, pressure, and equivalence radio, the decreases of inlet velocity and diameter of combustor, will lead to suppression of the inclinational instability.

Theoretical results of the Refs. [18,24,29] suggested that inclination is the manifestation of flame instability related with hydrodynamic effects. In contrast with Landau–Darrieus hydrodynamic instability of freely propagating flame, the hydrodynamic instability of filtrational gas combustion wave has specific feature. In particular, the instability was predicted only for solutions belonging to the increasing branch of $u_w(u_g)$ curve, where u_w is the velocity of combustion wave and u_g is the gas filtrational velocity. In Ref. [22], the existence of the critical wave length of perturbations corresponding to the minimal diameter of the channel was proposed. In the channel with diameter smaller than critical, flame is stable. This is supported by experiments [26]. The minimal diameter of the channel in turn strongly depends on derivative du_w/du_g, which is function of other parameters such as filtrational gas velocity, porosity, and equivalence ratio. The analysis based on $u_w(u_g)$ curve reveals to distinguish regions of instability and flame inclination in the regarded problem parameters space.

From the previous studies, we know that the flame shape in porous media is complex. Up to now, the flame front shape and its instability evolution in porous media are still not clear. There are lots of researches on the flame features and flame instabilities, however, it is still necessary to take more considerations on this topic. In some simulations [24,26], an inclined band with high temperature was assumed to be the initial inclinational flame in porous media combustion, while it cannot be used to explain the motivity of flame inclination. In this work, the flame instabilities of inclination and breakup are studied for different equivalence ratio experimentally. Subsequently, we present a two-dimensional and two-temperature numerical model in which no initial inclination angle is included. The model is used to evaluate the motivity of flame inclination using the inhomogeneous porosity within the packed bed or non-uniform gas mixture velocity or equivalence ratio at the burner inlet. Finally, the features of hydrodynamic instability of the filtration combustion are discussed and the heat loss effect on the inclination instability is evaluated.

2. Experimental apparatus and procedure

There are three parts in the experimental apparatus as shown in Fig. 1. They are combustion system, data collection system, and flow measurement and control system. In order to view the flame shape and the flame instability, a 600-mm-high quartz tube without thermal insulation is used. The inner diameter of the tube is 61 mm with a thickness of 3 mm. The tube is filled with 3 mm alumina pellets. To prevent flashback, additional strategy is made. A layer of 32 mm high ceramic foam of 40 ppi is set at the bottom of the tube, then a layer of 50 mm high alumina pellets of 2 mm diameter, finally a layer of 16 mm high the same kind ceramic foam.

The air and CH_4 are controlled and metered separately by two mass flow controllers and then mixed in a tank before their entering the combustor. The temperatures are measured by 12 K-type thermocouples. The thermocouples are inserted into the holes of the combustor and equally spaced with an interval distance of 20 mm. To prevent from destroying the structures of the packed bed, the thermocouples are inserted into the tube wall and their ends are along the inner surface of the tube. The temperature signals are digitized and transmitted to a computer by a TempTc/32B,