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Research Paper

Simulation of propane-air premixed combustion process in randomly packed beds

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HIGHLIGHTS

- A method is proposed to build real geometric structures of packed beds of particles.
- Propane-air premixed combustion process in randomly packed beds is simulated.
- Research flame characteristics during combustion process under different condition.
- Flame fractal dimension is calculated at different instants under different condition.
- Flame regimes under different condition are identified.

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Fractal dimension

ABSTRACT

Real geometric structures of randomly packed beds are modeled using the discrete element software LIGGGHTS. The wall-adapting local eddy-viscosity (WALE) model and the EBU-Arrhenius combustion model are used to simulate the propane-air premixed combustion process in the randomly packed beds, and the calculated results are compared with experimental data. The results reveal that the turbulence model and combustion model used in this paper are reasonable. Next, propagation velocity, area, mean vorticity and fractal dimension of a flame surface are calculated at various time points with different inlet velocities to investigate the changes in flame characteristics during the combustion process and the effect of increasing the inlet velocity. According to our results, the flame propagation velocity changes do not exhibit a clear trend over time. However, the variation trends of the two curves under the different inlet velocities are similar. In addition, the fractal dimension exhibits no obvious rule of increasing or decreasing during the combustion process. The area and mean vorticity of the flame surface increase with time. However, the rules of increase are not exactly the same. In addition, the flame regimes at various time points are identified. The results reveal that the turbulent premixed flames in a packed bed under two inlet velocities are concentrated in the thin reaction zone.

1. Introduction

Compared with traditional combustion in free space, combustion in porous media has many advantages, such as a higher burning rate, a wider range of capacity control, a wider limit of the fuel-lean flame and lower emission of pollutants [1]. Recently, based on the improved understanding of combustion in porous media, scholars have tried to use this technology in the production of fuel cells, internal combustion engines and gas turbines [2–4]. One-way and reciprocal flow premixed combustion in porous media as a basic combustion mode of mixed gas filtration combustion has been extensively studied. The relevant investigations have mainly concentrated on the temperature distribution, heat transfer and flame propagation speed emission characteristics in porous media [3–6].

The recent literature on empirical research on premixed combustion in packed beds is vast. Babkin et al. [7] performed experiments on premixed combustion in a porous structure. Their results indicate that the porous medium can substantially increase the speed of flame propagation. In their research, they divided filtration combustion into five groups according to combustion wave velocity: low-velocity filtration combustion ($0–10^{-4}$ m/s), high-velocity filtration combustion (0.1–10 m/s), sonic filtration combustion (100–300 m/s), low-velocity explosion filtration combustion (500–1000 m/s) and normal explosion filtration combustion (1500–2000 m/s). Brenner et al. [8] investigated a porous burner with intake and ignition systems on the top. Their experimental results reveal that the flame can be stabilized at the

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Nomenclature

A	empirical constants
B	empirical constants
D	diffusion coefficient ($m^2\,s^{-1}$)
D_2	fractal dimension (–)
Da	Damköhler number (–)
e	structural coefficient (–)
h	enthral ($J\,kg^{-1}$)
h_v	volume heat transfer coefficient ($W\,m^{-3}\,K^{-1}$)
k	turbulent kinetic energy ($m^2\,s^{-2}$)
k_{eff}	effective thermal conductivity ($W\,m^{-1}\,K^{-1}$)
l	integral turbulent length scale (m)
l_f	local laminar flame thickness (m)
M_C	molar mass of species C (g/mol)
M_P	molar mass of any product (g/mol)
M_R	molar mass of any reactant (g/mol)
Nu_v	Nusselt number (–)
P	pressure (Pa)
Pr	Prandtl Number (–)
Pr_{SGS}	subgrid Prandtl number (–)
R_C^A	reaction rate of chemical species C in the Arrhenius reaction ($kg\,m^{-3}\,s^{-1}$)
R_C	burning rate of chemical species C ($kg\,m^{-3}\,s^{-1}$)
R_C^T	turbulent reaction rate of C under limit of chemical mixture in EBU ($kg\,m^{-3}\,s^{-1}$)
Re	Reynolds number (–)
S_{hg}	energy source of gas phase ($W\,m^{-3}$)
S_{hs}	energy source of solid phase ($W\,m^{-3}$)
S_{ij}	tensor of strain rate (s^{-1})
s_L	local laminar flame speed (m/s)
Sc_{SGS}	subgrid Schmidt number (–)
t	time (s)
T	temperature (K)
T_g	temperature of gas (K)
T_{max}	maximum temperature on reaction region (K)
T_s	temperature of solid (K)
T_u	temperature of unburned gas (K)
u′	RMS velocity of turbulence pulsation (m/s)
u_i	velocity in i direction (m/s)
ν_C'	stoichiometric coefficient for species C (–)
ν_P'	stoichiometric coefficient for any product (–)
ν_R'	stoichiometric coefficient for any reactant (–)
x_i	rectangular coordinate parameter (m)
Y_P	mass fraction of any product (–)
Y_R	mass fraction of any reactant (–)

Greek symbols

λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
λ_{rad}	thermal conductivity obtained by the radiation ($W\,m^{-1}\,K^{-1}$)
λ_s	thermal conductivity for solid ($W\,m^{-1}\,K^{-1}$)
ρ	density ($kg\,m^{-3}$)
ε	turbulent dissipation rate ($m^2\,s^{-3}$)
ω_T	chemical reaction heat ($W\,m^{-3}$)
σ_{ij}	viscous stress tensor (–)
τ_{sgs}^{-1}	time scale of subgrid mixing rate (s^{-1})

Superscripts

–	physical space filtering
~	Favre filtering
A	Arrhenius reaction
T	turbulent reaction

Subscripts

g	gas
v	volume
eff	effective
C	species C
P	any product
R	any reactant
i	i direction
j	j direction
u	unburned gas
s	solid
rad	radiation
sgs	subgrid

interface of a two-layer porous medium. In addition, a total heat transfer coefficient was assumed to replace the effects of radiation, convection, solid heat conduction and gas dispersion in the system. Extending the single-temperature model, a two-dimensional steady-state model was established to analyze the combustion of premixed gas in porous media. The simulation result was in keeping with the experimental results. Lawrence et al. [9] constructed a packed bed combustor using alumina pellets with 5.6 mm diameter. The premixed combustion process of methane-air in the combustor was studied, and the dependency of the flame propagation velocity and the maximum combustion temperature on the equivalence ratio was discussed. The experimental results reveal that the equivalence ratio not only affects the magnitude of the flame propagation velocity but also its direction. When the equivalence ratio is in the range of 0.2–0.5, the flame propagation velocity is positive and decreases with an increasing equivalence ratio. When the equivalence ratio is in the range of 0.5–1, the flame propagation velocity is negative, the absolute value of the velocity increases with an increasing equivalence ratio, and the maximum values occur at the equivalence ratio of 1. Zhdanok et al. [10] used the superposition theorem of thermal and combustion waves to study the superadiabatic combustion process of methane-air in a packed bed both experimentally and theoretically. In the experiment, by adjusting the flow of premixed gas to superpose the combustion wave with the thermal wave, the researchers found that the flame temperature in the combustion chamber was approximately 2.8 times of the adiabatic temperature. Meng and Sun [11] report experiments using a one-dimensional bench-fixed bed combustion test with corn straw and investigated the effect on combustion characteristics of various corn straw lengths. n-Heptane combustion was researched by Yang and Zhou [12], who used porous micro combustors in two catalyst layouts. Rashidian et al. [13] used deflectors in a packed bed combustor to influence particle emissions and reduce radiation heat losses.

Recently, the interest in numerical methods and models in computational fluid dynamics (CFD) has been increasing. Such models are an important alternative to experiments. The models' cost is substantially lower, and they offer unlimited access to the porous structure and combustion processes [14–16]. Based on experiments, Bubnovich et al. [17] divided the combustion chamber into three parts: the preheat zone, the reaction zone and the product zone. Through analysis and experimentation, a set of formulas for calculating the combustion wave velocity, reaction zone width and ignition temperature in the packed bed was presented. Subsequently, Bubnovich [18] extended the single-temperature model to a two-temperature model in which the gas mixture and the pellets had their own temperatures. Thus, a more accurate model was established. The main modes of heat exchange during the premixed combustion process in porous media are (1) the thermal