Filtration Gas Combustion in High Porosity Fibrous Porous Media

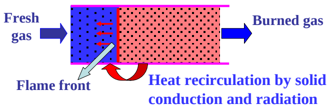
HaoLin YANG[1], Sergey MINAEV[2], Evgeniy GEYNCE[2], Hisashi NAKAMURA[1], Kaoru MARUTA[1]
1 Institute of Fluid Science, TOHOKU University, Japan
2 Institute of Theoretical and Applied Mechanics, Russian Academy of Sciences, Russia

Introduction

Excess enthalpy combustion (Weinberg, 1971)

- Strong internal heat recirculation → High efficiency
- Flame temperature decrease → Clean emission

Excess enthalpy combustion can be achieved by Combustion in porous media



Characteristics of combustion in porous media [2]:
Flame front: Upstream, downstream propagating or standing wave;
The maximum temperature: greater than, equal to, or less than the adiabatic combustion temperature.

Some issues related to combustion in porous media

Filtration gas combustion (FGC) may be unstable:
- Oscillation
- Pulsation
- Inclination
- Hot-spot
- Multiple reaction zone structure

Instabilities will lead to unstable operation of devices and limit the widespread use of FGC.

The earlier works focused mainly on FGC properties in ceramic / metallic balls or foams

Type	Alumina sphere	Steel sphere	Ceramic sphere	Sand	Fine fiber
Diameter	3, 5.6 mm	3, 6 mm	2-3, 6.5 mm	0.56 mm	4 μm
Porosity	0.4	0.2 – 0.5	0.36 - 0.45	0.25	> 0.9


Tube packed with fibrous porous media

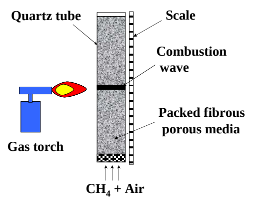
Objectives

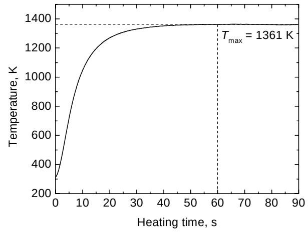
To investigate the basic characteristics and special phenomena for gas combustion in high-porosity fibrous porous media.

How is FGC in this kind of fine structure porous media?


Fibrous porous media

Experiments





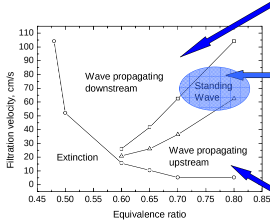
Temperature history of the external wall at heating position

Ignition method: Heated by gas torch
Heating time: Fixed at 60 seconds

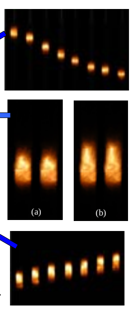
Experimental parameters

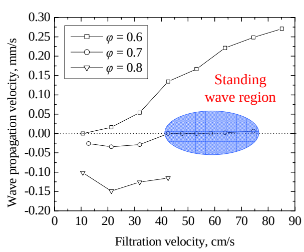
Fuel: Methane/Air
Tube: Inner diameter D = 4.8, 8, 9.8, 18.5 mm, Length = 300mm
Fiber type: Al_2O_3(72%), SiO_2(28%)
Mean diameter of fiber: 4 μm
Thermal conductivity: 0.28 (W/mK) at 1173 K
Bulk density: 0.58 g/cm^3
Porosity: 0.94

Standing wave region observed in experiment



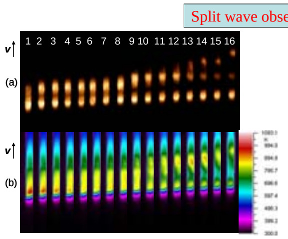
Experimental stability diagram for filtration gas combustion in fibrous porous media at D = 18.50 mm.



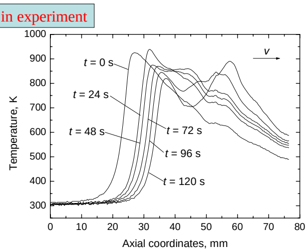


Experimental wave propagation velocity for different equivalence ratios at D = 18.50 mm.

Split wave observed in experiment



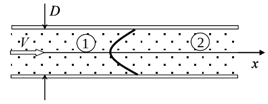
Direct photos (a) and temperature profiles (b) of split waves structure as D = 4.80 mm, ϕ = 0.8, and v = 147 cm/s. The time step of the sequential pictures was 8 sec.



Temperature distributions at the centerline of the tube surface at different time.

Analytical method

1D analysis within frame of two-temperature model of filtration gas combustion. Solid radiative heat transfer was included in the model.



Scheme of the combustion wave in porous media. 1- unburned gas, 2- burned gas.

Solid and gas temperature equations

$$\begin{cases} \rho_s c_s\left(\frac{\partial T_s}{\partial t}-u\frac{\partial T_s}{\partial x}\right)=\frac{\partial}{\partial x}\left(\lambda_r\frac{\partial T_s}{\partial x}\right)+\frac{2\alpha\varepsilon(T_g-T_s)}{d_0(1-\varepsilon)}+\frac{2\tilde{\alpha}(T_0-T_s)}{D}-\frac{\sigma k_g}{D(1-\varepsilon)}(T_s^4-T_0^4) \\ \rho_g c_g\left(\frac{\partial T_g}{\partial t}+(v-u)\frac{\partial T_g}{\partial x}\right)=\lambda_g\frac{\partial^2 T_g}{\partial x^2}+\frac{2\alpha}{d_0}(T_s-T_g)+SQW(C,T_g) \end{cases}$$

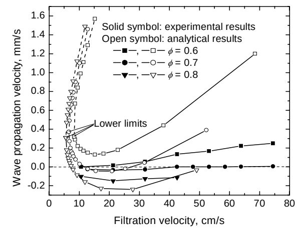
Concentration of the deficient reactant

$$\frac{\partial C}{\partial t}+(V-u)\frac{\partial C}{\partial x}=\kappa\frac{\partial^2 C}{\partial x^2}-SW(C,T_g) \quad W(C,T_g)=U_b\exp\left(\frac{T_a}{2T_b}\left(\frac{T-T_b}{T}\right)\right)\delta(x-x_f)$$

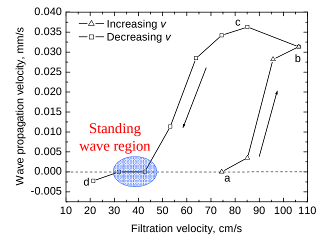
The boundary conditions for equations

$T_g = T_s = T_0$ as $x \to \pm\infty$;
$C = 1$ as $x \to -\infty$.

Discussion



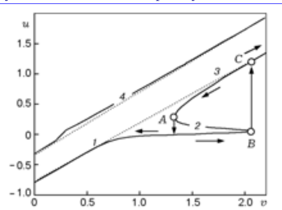
Comparison of wave propagation velocities between analytical and experimental results for D = 18.50 mm.



Wave propagation velocity as a function of the filtration velocity at D = 11.85 mm, ϕ = 0.7.
Started from point a with increasing flow velocity; decreasing flow velocity from point b till point d.

- U shaped relationship was obtained (Babkin, et al. 1983)
- ϕ = 0.6: flame propagates downstream
- ϕ = 0.7, 0.8: upstream propagating flame formed in medium velocity
- The region of standing wave has not been obtained by analytical model due to complexity of FGC

- a→b: v_f increases with filtration velocity
- c→d: v_f decreases with filtration velocity
- v_f during the process a→b is higher than the corresponding v_f during the process c→d
- Is there a hysteresis effect?



Dependence of flame propagation velocity u on the filtration velocity v in the tube with $Pe = 1.1Pe_{cr}$. Curves 2 and 4 are unstable branches. Curves 1 and 3 are stable branches and A, B, and C are the points of bifurcation (Zamashchikov and Minaev, 2001).

Relation between experimental and analytical results

a→b in experiment ==> B→C in analytical results
c→d in experiment ==> C→A in analytical results

The standing wave region observed in high-porosity fibrous porous media is likely similar to the hysteresis phenomena observed by Zamashchikov (1997) in experiments on gas combustion in narrow tubes with inner diameter larger than the critical diameter.

Conclusions

- Between upstream and downstream propagating regimes, a specific standing wave regime was observed, whereas only one standing wave point existed in other ordinary porous media.
- The general analysis by 1D two-temperature model showed qualitative agreement with experimental results in the upstream propagating regime.
- The standing wave in fibrous media was regarded principally as another illustration of hysteresis phenomena which was first reported in narrow tube.
- The characteristics of filtration gas combustion in fibrous porous media were described very well by the combination of classical combustion theories in tubes at $Pe < Pe_{cr}$ for upstream propagating regime and at $Pe > Pe_{cr}$ for both standing and downstream propagating regimes.
- The split wave might be due to nonuniform heat loss on inclined wave front and a leakage of incomplete burned mixture through the original wave front.

References

1. Weinberg, F. J. (1971) Combustion temperatures: the future. *Nature*, **233**, 239.
2. Howell, J. R., Hall, M. J., and Ellzey, J. L. (1996) *Prog. Energy Combust. Sci.*, **22**, 121.
3. Babkin, V. S., Drobyshevich, V. I., Laevskii, Yu. M., et al. (1983) *Combust. Explos. Shock Waves*, **19**, 147.
4. Zamashchikov, V. V. and Minaev, S. S. (2001) *Combust. Explos. Shock Waves*, **37**, 21.
5. Zamashchikov, V. V. (1997) *Combut. Flame*, **108**, 357.