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Experimental investigation on peculiarities of the filtration combustion of the gaseous fuel-air mixtures in the porous inertia media

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Abstract

This study investigates peculiarities of the filtration combustion (FC) of the gaseous fuel-air mixtures in a porous inertia media (PIM). Combustion wave velocities and temperatures were measured for hydrogen-air, propane-air and methane-air mixtures in the PIM at different mixture filtration velocities. It is shown that the dependences of the combustion wave velocities on the equivalence ratio are V-shaped. It was further confirmed that the FC in the PIM has more contrasts than similarities with the normal homogeneous combustion. One of the interesting observations in the present study, which is not common in normal homogenous combustion, is the shifting of the fuel-air equivalent ratio at the minimum combustion wave velocity from the stoichiometric condition ($\phi = 1$). For a hydrogen-air mixture, the fuel-air equivalence ratio at the minimum combustion velocity shifts from the stoichiometric condition to the rich region, while for the propane-air and methane-air mixtures the fuel-air equivalence ratio at the minimum combustion velocity shifts toward fuel-leaner conditions. The measured maximum porous media temperatures in the combustion waves are found to be weakly dependent on the mixture filtration velocities. In general, the effects of the mixture filtration velocities on the measured maximum porous media temperatures are not significant.

Keywords: Filtration combustion; Porous media; Hydrogen; Methane; Propane

1. Introduction

Filtration combustion (FC) occurs when exothermic waves interact within a porous media as a gas mixture is infiltrated into the reaction zone. The solid porous media may be a condensed fuel (porous media with reactive components) with the gas carrying oxidizer flowing through the pores or the solid porous inertia media (PIM) with the filtrating gas consisting of both fuel and oxidizer. In either case the characteristics of combustion differ substantially from normal homogeneous combustion. The difference is mainly attributed to the heat transfer between gas and solid, the turbulent structure of the gas flow through the porous media and heat exchange in the gas phase. As the gas mixture is ignited inside the porous media, the combustion enthalpy from the combustion reaction is absorbed by the solid matrix, which transfers the heat to the next layer of PIM solid bodies immediately above or below the combustion zone. Hence, the conduction heat transfer is enhanced along the solid phase compared, to the gas phase and radiation exchange between particles. The combined effects of conduction, radiation and surface convection cause substantial preheating of the incoming reactants. This recuperation is an internally self-organized process and is responsible for the excess enthalpy combustion process. This process was first developed by Wienberg [1] and Egerton, et al. [2]. They demonstrated theoretically that excess enthalpy

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combustion is possible if the heat from the hot combustion products is re-circulated to the incoming reactants. Takeno and Sato [3] and Takeno *et al.* [4] subsequently showed that theoretically inserting the porous solid into the flame zone provided the necessary heat feedback to produce the super-adiabatic combustion. Since then, there has been extensive research on combustion in the porous media. Babkin and co-workers [5-8] extensively studied the FC in the PIM. According to their results, the FC can be classified as high-velocity (HV) FC, low velocity (LV) FC, sub-sonic FC and other regimes depending mainly on the combustion wave velocity relative to the solid phase and peculiarities of heat and mass transfer in the system. HVFC regime has a characteristic speed of meters per second and is controlled by heat and mass transfer in the gas phase and to a lesser extent by the gas thermal interaction with the porous body. On the other hand, the LVFC regime is characterized by the speed of order of 0.1 mm per second and is controlled by the intensive inter-phase heat exchange and solid-phase heat conduction.

Depending on the gas filtration velocity, propagation of the combustion wave in the LV regime can propagate at the downstream, upstream or be at a standstill. The downstream propagation of the combustion waves, co current to the gas filtration velocity, leads to the combustion in the super-adiabatic regime with temperature exceeding the adiabatic temperatures [5, 9], while the upstream wave propagation, counter-current to the gas filtration velocity, results in the under-adiabatic combustion temperatures [5, 9]. Super-adiabatic combustion can extend the lean flamm-ability limit to the region of the super-lean of any fuel and it allows in principle to burn any low calorific-value fuel. These unique properties of the FC waves which are absent from a conventional homogeneous flame are related to the presence of two or more phases, motion of reactants and intense heat and mass transfer in the combustion wave zones. FC has become an attractive process in many applications due to these properties. Examples of applications of the FC in the PIM are recycling (oxidation) of the harmful gases, combustion of a super-lean fuel mixture in the super-adiabatic combustion mode, treatment of catalysts with an adiabatic wave, etc. The properties of the FC wave strongly depend on the operating parameters of the combustion system, such as fuel-air equivalence ratio, mixture filtration velocity through the PIM, and characteristics of the PIM bed, such as porosity, mean grain size, reactivity in relation to combustion, thermophysical properties of the PIM bed (density, thermal capacity and thermal conductivity)[5, 6, 8]. Changing any of these parameters will affect the FC wave characteristics. Therefore, the objective of the present contribution is to study experimentally the pe-culiarities of the FC of the gaseous fuel-air mixtures in the PIM. In this study, these peculiarities are investigated by analyzing the combustion waves and PIM temperature variations.

2. Experimental apparatus and setup

A quartz reactor was designed to study peculiarities of the FC of the different gaseous fuel-air mixtures in the PIM. Fig. 1 shows the experimental set-up, which consisted of a vertical quartz tube with 50 mm external diameter, 1.5 mm thickness and 410 mm long, insulation materials, PIM bed, thermocouples and fittings for the gaseous-air mixtures supply. The test section, which is 350 mm in length, was filled with randomly packed PIM beds of solid carborundum. In the current study three gaseous fuel-air mixtures: hydrogen-air mixture, propane-air mixture and methane-air mixture were used. In the hydrogen-air mixture experiments, *1–2* mm PIM sphere sizes and mixture filtration velocity of *1.45* m/s were used. For the propane-air mixture experiments, *2–3* mm sphere sizes and three filtration velocities (v = *0.52*, *0.66*, and *0.79* m/s) were used. Finally, in the case of methane-air experiments, *2-3* mm PIM sphere sizes and four filtration velocities (v = 0.*25*, *0.3*, *0.45*, and *0.6* m/s) were used. To ensure minimum heat loss, the quartz tube was wrapped with an econtronics ceramic fiber blanket, which can withstand continuous heating up to a maximum temperature of 1640°C. The insulation blanket was slit on one side for convenient observation of the combustion wave structure formation during the combustion process. The flame propagation over the PIM beds was photographed by using a digital camera. A chromel-alumel thermocouple was inserted between spheres for the gas temperature measurement. The temperature profile of the solid media was monitored with the chromel-alumel thermocouple inserted in the thin-walled quartz capillary. Signals from the thermocouples and digital camera were continuously digitized and stored by the PC-based data acquisition system. The

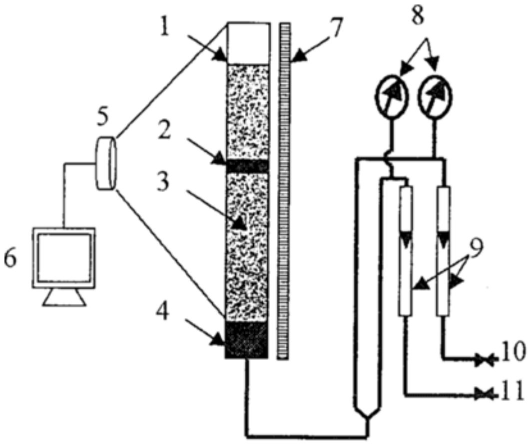


Fig. 1. Experimental Set up (1) quartz tube; (2) combustion zone; (3) PIM; (4) flame arrestor; (5) camera; (6) computer; (7) laboratory ruler; (8) pressure gauges; (9) flow meters; (10) and (11) methane and air supply.

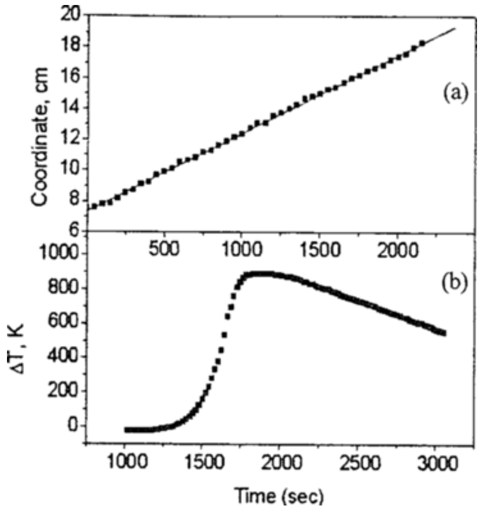


Fig. 2. Typical dependencies of wave front coordinate (a) and increment of porous medium temperature (b) on time (mixture concentration:70% H_2+air).

combustible mixtures were made by blending the gaseous fuels and air through the rotameter-type flow meters and were supplied to the quartz reactor by a mixing tube.

The following experimental procedures were adopted. The first step was to set up a free stream flame located at the exit of reactor above the leading edge of the PIM. At this stage, ignition of the gaseous fuel-air mixture occurs without the influence of the PIM. Due to the difficulty of ignition of the gaseous fuel-air mixtures at the normal conditions, ignition was initiated with the rich gaseous fuel-air mixtures. During this stage the rich gaseous fuel-air mixtures were supplied for about 1~2 s. After flame propagated into the PIM bed and combustion wave developed into it, the experimental conditions were adjusted to the required settings. Finally, after a relaxation time of about 2~3 min, the temperature of both the gaseous fuel-air mixture and PIM solid bodies, position (coordinate) of the FC wave, flowrates and pressures of both gaseous fuel and air were recorded.

3. Experimental results

Fig. 2 shows typical records of the coordinates of the combustion wave front and temperature of the porous medium in the combustion wave versus time. The coordinate records have a more or less extended (*5–10* min) unsteady segment, which corresponds to a transition from the regime of wave "placement" to the regime being studied, and a linear segment, which corresponds to steady-state wave propagation (see Fig. 2(a)). The steady state combustion wave velocity (u) was determined from the linear segment, while the maximum temperature of the porous medium in the combustion wave ($T_{m,exp}$) was determined from temperature records (see Fig. 2(b)). In addition, temperature recorded data and measured wave velocities were used to obtain the temperature distribution in the combustion wave $T(x)$.

The combustion wave velocity of the hydrogen-air mixture at the filtration velocity of *1.45* m/s as a function of an equivalence ratio is shown in Fig. 3. In this figure, the super-adiabatic and under-adiabatic regions are well defined since they correlate to the direction of the wave propagation. In the lean regime of combustion, the super-adiabatic region corresponds to the downstream propagation, concurrent to the filtrating mixture. There, the fastest combustion wave velocity of *0.0488* cm/s at $\phi \approx 0.011$ is recorded. As the equivalence ratio increases, the propagation speed decreases substantially to where the wave is moving at a speed of *0.00508* cm/s with the equivalence ratio of about *0.425* and finally to a standstill at *0.495*. At this point, the combustion and adiabatic temperatures coincide. In the lean regime, between $0.011 < \phi < 0.425$ corresponds to the super-adiabatic region. Above $\phi \approx 0.495$, the wave propagates in the opposite direction. In propagating against the filtrating mixture, the minimum (maximum in the terms of absolute values) combustion wave velocity of *-0.0784* cm/s

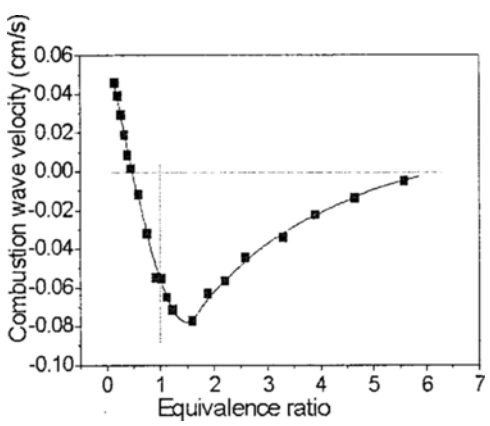


Fig. 3. Combustion wave velocity of the hydrogen-air mixture as a function of fuel-air equivalence ratio.

occurs at $\phi \approx 1.5$, beyond this point, the wave begins to slow down up to *0.0027* cm/s at $\phi = 5.85$.

Fig. 4 displays the combustion wave velocity of the propane-air mixture as a function of the fuel-air equivalence ratio for the different filtration velocities. It is seen that the dependence of the combustion wave velocity against the equivalence ratio has a *V*-shape. The combustion wave velocity values (absolute values), generally increase with decreasing the mixture filtration velocity at an equivalence ratio below the stoichiometry values ($\phi=1$). Beyond the stoichiometric values, the combustion wave velocity values (absolute values) increase with increasing the mixture filtration velocity. Here again, in the fuel leaner region of combustion, the super-adiabatic combustion corresponds to the downstream propagation of the combustion wave concurrent to the movement of filtrating mixture. In this region, the overall fastest combustion wave velocity of about *0.00795* cm/s is recorded at $\phi \approx 0.36$ for the mixture filtration velocity of *0.79* m/s. As equivalence ratio increases, the combustion wave propagation speed decreases substantially to where the wave is moving at a speed of *0.000134* cm/s with $\phi = 0.58$ and finally to a standstill at $\phi \approx 0.6$. At this point the combustion and adiabatic temperatures coincide. The lean region between $0.36 < \phi < 0.6$ corresponds to the super-adiabatic combustion regime. Above $\phi \approx 0.6$, the wave propagates in the opposite direction. In propagating against the filtrating mixture, the minimum (maximum in terms of absolute values) combustion wave maximum velocity of -*0.00857* cm/s at $\phi \approx 0.98$ is registered, beyond this point the wave begins to slow down. It reaches a standstill at

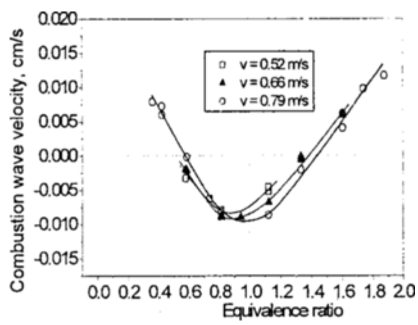


Fig. 4. Combustion wave velocity of the propane-air mixture as a function of equivalence ratio for three filtration velocities.

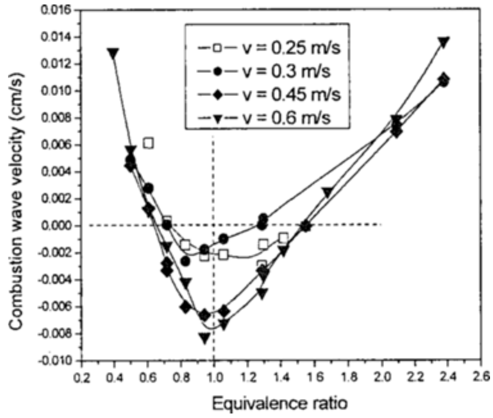


Fig. 5. Combustion wave velocity of the methane-air mixture with respect to equivalence ratio for four filtration velocities.

about $\phi = 1.44$, where it once again reverses direction and moves concurrent to the filtrating mixture. A steep rise of the velocity profile in the rich super-adiabatic region is observed for $1.44 < \phi \leq 1.875$. The velocity reaches a value of *0.0118* cm/s at $\phi = 1.875$. In the case of the mixture filtration velocity = *0.66*, the flame propagates countercurrent to the reactant flow direction. Here, the fastest combustion wave velocity of about -*0.00868* cm/s is recorded at $\phi \approx 0.81$; beyond this point the wave begins to slow down. It reaches a standstill at about $\phi \approx 1.39$ where it once again reverses its direction and moves concurrent to the filtrating mixture. A steep rise of the velocity profile in the rich super-adiabatic region is observed between $1.39 < \phi \leq 1.6$. A maximum velocity of about *0.0062* cm/s is achieved at $\phi \approx 1.6$. For the filtration velocity of *0.52* m/s, flame propagates countercurrent to the reactant flow direction. The maximum combustion velocity of about -*0.0085* cm/s is achieved at $\phi = 0.81$.

Fig. 5 displays the combustion wave velocity of the methane-air mixtures as a function of the fuel-air equivalence ratio for the different mixture filtration velocities. It is seen that the dependence of the combustion wave velocity against equivalence ratio has a *V*-shape. This trend is observed for all flames. In the ultra lean combustion region ($\phi = 0.39 \leq 0.64$), the super-adiabatic combustion corresponds to the downstream propagation of the combustion wave concurrent to the filtrating mixtures. From $\phi \approx 0.71$ to *1.299* (v = *0.3* m/s), and $\phi \approx 0.71$ to *1.55* (v = *0.45* and *0.6* m/s), the under-adiabatic combustion corresponds to the upstream propagation of the combustion waves countercurrent to the filtrating mixtures. Beyond these values, flame propagates concurrent to the filtrating mixtures (rich super-adiabatic combustion region). Furthermore, the figure shows that the shifting of the minimum values (maximum value in terms of absolute at the under-adiabatic region) of the combustion wave velocity curve from stoichiometric condition ($\phi = 1$) decreases when the mixture filtration velocity is increased from *0.3* to *0.6* m/s. This is because the increase of the mixture filtration velocity reduces the heat loss; thus, a higher flame speed and shifting of the minimum values of the wave velocity curves are observed. For all tested mixtures, the overall maximum combustion wave velocity of *0.01286* cm/s at $\phi \approx 0.39$ is noticed in the lean fuel super-adiabatic region, while at the rich fuel super-adiabatic region, the overall maximum combustion wave velocity of *0.0136* cm/s is observed at $\phi \approx 2.38$ for the mixture filtration velocity of *0.6* m/s. In propagating against the filtrating mixtures, the maximum combustion wave velocity values occur between $\phi = 0.82$ *and* 0.95. From here, an overall maximum combustion velocity of *0.00852* cm/s at $\phi = 0.95$ is observed when the mixture filtration velocity is *0.6* m/s. Beyond this region the combustion wave velocity values drops significantly.

Fig. 6 depicts the combustion wave velocity of the methane-air mixture as a function of the fuel-air equivalence ratio for two different porous body particle sizes. It is seen that the dependence of the combustion wave velocity against equivalence ratio has also a *V*-shape. This trend is observed for both flames. It is known that the porous body particle size is an important parameter defining heat and mass transfer in the porous media and FC dynamics. As the porous body particle size is increased, an increase in the combustion wave velocity propagating against the filtrating mixture is noticed. A maximum combustion wave velocity of *-0.004* cm/s occurs at $\phi \approx 0.942$ for $d = 6.5$ mm; beyond this point the wave begins to slow down. It quenches at $\phi \approx 1.29$. For $d = 2\text{-}3$ mm, in the lean super-adiabatic combustion region; the fastest combustion wave velocity of about *0.0049* cm/s at $\phi \approx 0.5$ is observed. As the equivalence ratio increases, the propagation velocity decreases substantially to a standstill at $\phi = 0.71$. At this point, the combustion and adiabatic temperatures coincide. In the lean regime, between $0.5 < \phi < 0.71$ corresponds to the super-adiabatic region. Above, $\phi = 0.71$ the wave propagates in the opposite direction. In propagating against the filtrating mixture, the minimum (maximum in terms of absolute values) combustion wave velocity of -0.00178 cm/s occurs at $\phi = 0.942$; beyond this point the wave begins to slow down. It reaches a standstill at $\phi = 1.29$ where it once again reverses its direction and moves concurrent to the filtrating mixture. A steep rise of the linear velocity profile in the rich super-adiabatic region is observed between $1.3 < \phi < 2.33$; and the maximum combustion velocity value of *0.0106* cm/s is reached at $\phi = 2.38$. The shifting of the minimum values (maximum in terms of absolute values at the under-adiabatic region) of the combustion wave velocity curve of the methane-air mixture with the *6.5* mm size porous body particles value from stoichiometric condition is smaller than that with the 2~3 mm size porous body particles.

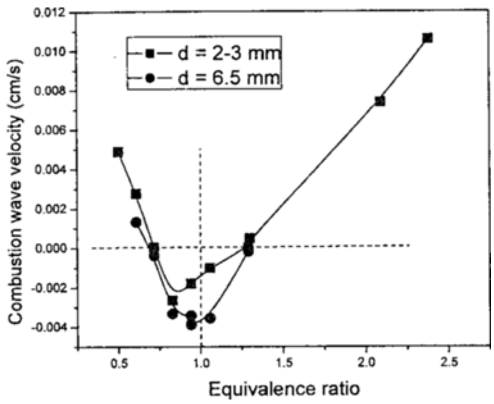
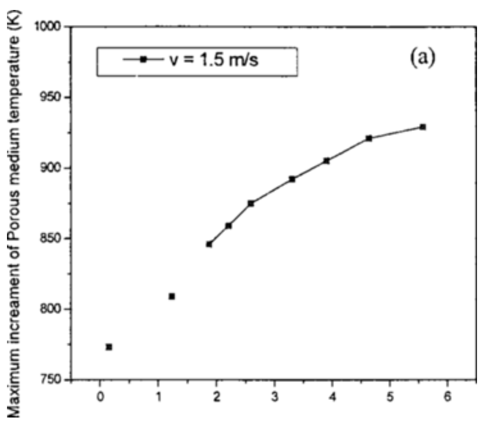


Fig. 6. Combustion wave velocity of the methane-air mixture with respect to equivalence ratio for two porous body particle sizes.

Fig. 7 shows experimental values of the maximum heating temperature of the porous medium in the combustion wave versus equivalence ratio. The heating



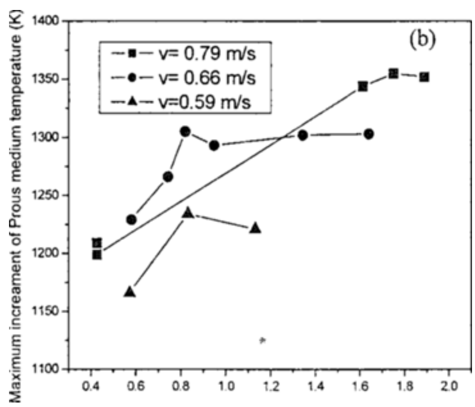


Fig. 7. Measured temperatures of the porous medium versus equivalence ratio: (a) H_2+air mixtures; (b) C_3H_8+air mixtures (c) CH_4+air mixtures.

temperature value was determined as $\Delta T_{m,exp} = T_{m,exp} - T_0$, where $T_{m,exp}$ is the maximum value on the measured temperature profile in the porous medium, and T_0 is the room temperature. We note that for all mixtures studied, the heating of the porous medium depends weakly on equivalence ratio. The studied mixture data also show a weak dependence of the heating on the mixture filtration velocity.

4. Analysis and discussion

Analysis of data obtained was based on a simplified one-temperature model of the FC, corresponding to the heat exchange between gas and porous media solid bodies.

The expression for an adiabatic FC wave propagation velocity (u) was obtained in [5] dependent on gas mixture composition

$$u \approx u_{th} \left[1 + \frac{R(T_b - T_0)}{E} \ln \frac{G u_{th} Ze}{\kappa_s k_0 \rho_{gb}} - \frac{R^2 (T_b - T_0) T_0}{E^2} \ln^2 \frac{G u_{th} Ze}{\kappa_s k_0 \rho_{gb}} \right] \quad (1)$$

Here $u_{th} = \frac{c_g \rho_g v m}{c_s \rho_s (1-m)}$ is the thermal velocity of;

$Ze = \frac{E(T_b - T_0)}{RT_b^2}$ is Zeldovich number.

Mixture composition is characterized by the adiabatic heating up value: $T_b - T_0 = Q / c_g$

The second term in Eq. (1) under typical values of the experimental parameters is always negative. The third term in the brackets in Eq. (1) is also negative. Then one can see from Eq. (1) that at a constant filtration velocity, the minimum value of the combustion wave velocity is achieved at the maximum adiabatic heating up value, i.e., at the stoichiometric gaseous fuel-air mixture condition. However, according to the experimental data in Figs. 3~5, the minimum dependence of combustion wave velocity against equivalence ratio ($u(\phi)$) is shifted to the richer region for the hydrogen-air mixture and leaner region for methane-air mixture and propane-air mixture, respectively. In addition, from Figs. 3~5, it is evident that the dependence of $u(\varphi)$ for the given filtration velocity becomes very weak in the region of the minimum velocities, which considerably reduces the accuracy of determination of φ_{min}.

The shifting of equivalence ratio at the minimum values (maximum in terms of absolute values in the under-adiabatic region) of the combustion wave velocity from the stoichiometric condition ($\phi = 1$) versus the mixture filtration velocity is shown clearly in Fig. 8. It is evident that the shifting increases with decreasing filtration velocity for both propane-air and methane-air mixtures. However, for the methane-air mixture at a very low mixture filtration velocity of 0.25 m/s, the shifting of equivalence ratio at the minimum combustion wave velocity decreases abruptly to almost zero. We note that the mixture filtration velocity of 0.25 m/s is the lower limit for combustion of the methane-air mixtures for given tube and porous media solid bodies.

These observed properties of the FC wave velocity characteristics in the rich hydrogen-air mixture and lean propane-air and methane-air mixtures are similar to the ones normally observed in the laminar flames

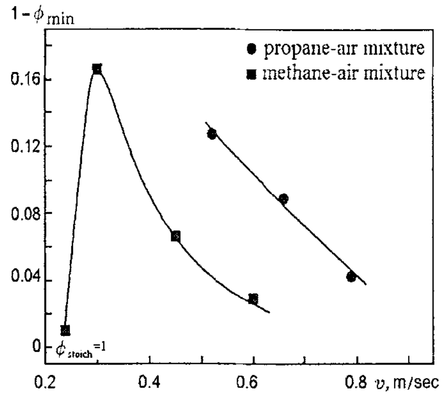


Fig. 8. Effects of filtration velocity on the shifting of the combustion wave velocity from stoichiometric mixture condition

of the preheated homogenous mixtures and due to the Lewis number effects. Among such are, for example, variation in the laminar burning velocity due to flame front curvature [10], the development of flame instability relative to the front curvature [11] and the formation of cellular flame structure [12].

5. Conclusions

Experimental measurements of the FC wave velocities and combustion temperatures of the gaseous fuel-air mixtures in the PIM were carried out. With methane as fuel, four filtration velocities (v = *0.25*, *0.3*, *0.45*, and *0.6* m/s) were selected, while with propane as a fuel, three filtration velocities (v = *0.52*, *0.66*, and *0.79* m/s) were selected, and finally for hydrogen as fuel, one velocity (v = *1.45* m/s) was selected. It is shown that the dependences of the combustion wave velocity on equivalence ratio are V-shaped. It was further confirmed that porous media combustion has more contrasts than similarities with the conventional homogeneous combustion. Propagating in the same direction as the incoming filtrating mixture, the combustion wave velocity slows down with increasing equivalence ratio and finally moves to a standstill where adiabatic and combustion temperature equalizes in the same said region. As the equivalence ratio increases further, the combustion waves propagating against the incoming filtrating mixtures reach minimum velocities (maximum in terms of absolute values at the under-adiabatic combustion region). Then, they slow down and reach a standstill at different equivalence ratios. Once again the waves reverse direction and move concurrent to the incoming filtrating mixture. One interesting observed behavior in the current study is the shifting of equivalence ratio at the minimum (maximum in terms of absolute values in the under-adiabatic region) combustion wave velocity from the stoichiometric condition ($\phi = 1$). For the hydrogen-air mixture, the fuel-equivalence ratio at the minimum combustion velocity shifts from the stoichiometric condition to the richer region, while for the propane-air and methane-air mixtures shift toward fuel-leaner conditions. The measured maximum temperatures in the combustion waves are found to be weakly dependent on the mixture filtration velocity. In some cases, small effects of the mixture filtration velocities on porous medium temperature are noticed.

Acknowledgements

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Nomenclature

c	:	Specific heat capacity , J/(m^3.K)
E	:	Activation energy of one-step chemical reaction, kJ/kmol
$G = \rho_g v$	:	Mass flow rate of the gas, kg/m^2.s
k_0	:	Pre-exponent
m	:	Porosity of porous medium
Q	:	Effective heat release of combustion, J
R	:	Gas constant, kJ/kg. K
T_b	:	Combustion temperature, K
T_0	:	Initial temperature, K
u	:	Combustion wave velocity, cm/s
u_{th}	:	Thermal wave velocity, cm/s
v	:	Mixture filtration velocity, cm/s
Ze	:	Zeldovich Number
λ	:	Thermal heat conductivity, W/m.K
ρ_{gb}	:	Density of gas mixture at temperature (T_b), kg/m^3
$\kappa_s = \frac{\lambda_s}{c_s \rho_s}$	:	Thermal diffusivity of porous medium, m^2/s
ρ_g	:	Density of the gas, kg/m^3

Subscripts

b	:	Combustion temperature

g	:	Gas
s	:	Porous medium
gb	:	Density of gas mixture at temperature (T_b)
0	:	Initial temperature
th	:	Thermal

References

[1] F. J. Weinberg, Combustion in heat-recirculating burners, In: Weinberg FJ, editor. *Advanced combustion methods*. New York: Academic Press, (1986) 183-236.

[2] A. Egerton, K. Gugan and F. J. Weinberg, Mechanisms of Smouldering in cigarettes, *Combust. Flame.* 7 (1963) 63-78.

[3] T. Takeno and K. Sato, An excess enthalpy theory, *Combust. Sci. Tech.* 20 (1979) 73-84.

[4] T. Takeno, K. Sato and K. Hase, A theoretical study on an excess enthalpy flame. In: *Proc. 18 Symp. (Int.) on Combustion*, The Combustion Inst., Pittsburgh, (1981) 465-472.

[5] Yu. M. Laevskii and V. S. Babkin, Filtration combustion of gases. In: Matros Yu, Editor. Propagation of heat waves in heterogeneous media, Novosibirsk: *Nauka.* (1982) 108-45.

[6] N. A. Kakutkina, and V. S. Bubkin, Characteristics of stationary spherical waves of gas combustion in inert porous mediums, *Combust. Explos. Shock Waves.* 34 (1998) 150-159.

[7] S. I. Potytnyakov, V. S. Babkin Yu. M. Laevskii, and V. I. Drobyshkevich, Thermal structure of an in situ gas combustion wave, *Combust. Explos. Shock Waves.* 21 (2) (1985) 19-25.

[8] A. A. Korzhavin, V. A. Bunev, V. S. Babkin, Dynamics of gaseous combustion in closed system with an inertia porous medium, *Combust. Flame.* 109 (4) (1997) 507-520.

[9] S. Zhdanok, L. A. Kennedy and G. Koester, Superadiabatic combustion of methane air mixtures under filtration in a packed bed, *Combust. Flame* 100 (1-2) (1995) 221-223.

[10] G. Markstein (ed.), *Nonsteady Flame Propagation*, Pergamon Press, Oxford (1968).

[11] B. Zel'dovich, G. I. Barenblatt, V. B. Librovich and G. M. Makhviladze, *The Mathematical Theory of Combustion and Explosions*, Plenum, New York (1985).

[12] B. Lewis and G. von Elbe, *Combustion, Flames, and Explosion of Gases*, Academic Press, Orlando (1951).