New Properties of High Velocity Regime of Filtration Gas Combustion

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1 Introduction

Filtration gas combustion (FGC) as the process of gas phase combustion in an inert porous medium includes a number of steady-state regimes of combustion waves propagation. They are Low Velocity Regime (LVR), u~10^{-4} m/s; High Velocity Regime – HVR, u~1-10 м/с; Sonic Velocity Regime – SVR, u~100 m/s; regime of Low Velocity Detonation and Normal Detonation with heat and momentum losses – LVD, D~800 m/s; ND, D~(1-0.9)$D_{C\text{-}J}$ [1]. Some aspects of FGC are studied in detail. However a number of principal problems are unclear [2]. One of them is the problem of effect of forced flow of combustible gas on combustion characteristics in HVR, which is characterized with absence of baric wave in the combustion zone and characteristic size of the channel of a porous medium d more than critical diameter d_{cr}.

Really, practically all up to date researches of HVR deal with natural combustible gas flows that is with flows due to combustion processes themselves. In these cases the filtration velocity is been function of the processes is not a determining parameter. Therefore the existing equations for determination wave velocity and critical condition do not include filtration velocity [3]. This circumstance generated the point of view that in HVR the main interphase interaction is the forced one (flow turbulization) and thermal interaction is not influence directly on chemical conversion. However the theory of filtration gas combustion and the analysis show that in principle there is possible in HVR strong thermal interphase interaction in the region of chemical reactions when the value of filtration velocity is close to the burning one [4]. To clarify the role and mechanism of participation of forced flow at FGC in HVR there was carried out an experimental investigation of the combustion character, steady and nonsteady processes, regimes transitions, the characteristic of counterflow, stabilized and coflow combustion waves under variation of filtration velocity.

2 Experiments, results and discussion

The experiments were carried out in wide quartz and steel tubes with a porous medium and also in the model narrow solitary quartz tubes with inner diameters of 3.2, 5.1 and 7.0 mm. As porous media there were utilized ceramic (Al_2O_3, d_b ~ 15 mm) and steel polished balls (d_b=9.5 and 12.7 mm). The premixed methane- and propane-air mixtures in the wide range of the equivalence ratio were used.

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All the experiments carried out at room temperature and atmospheric pressure. For recording of flame characteristics there were used photodiodes, high speed video framing and direct photography.

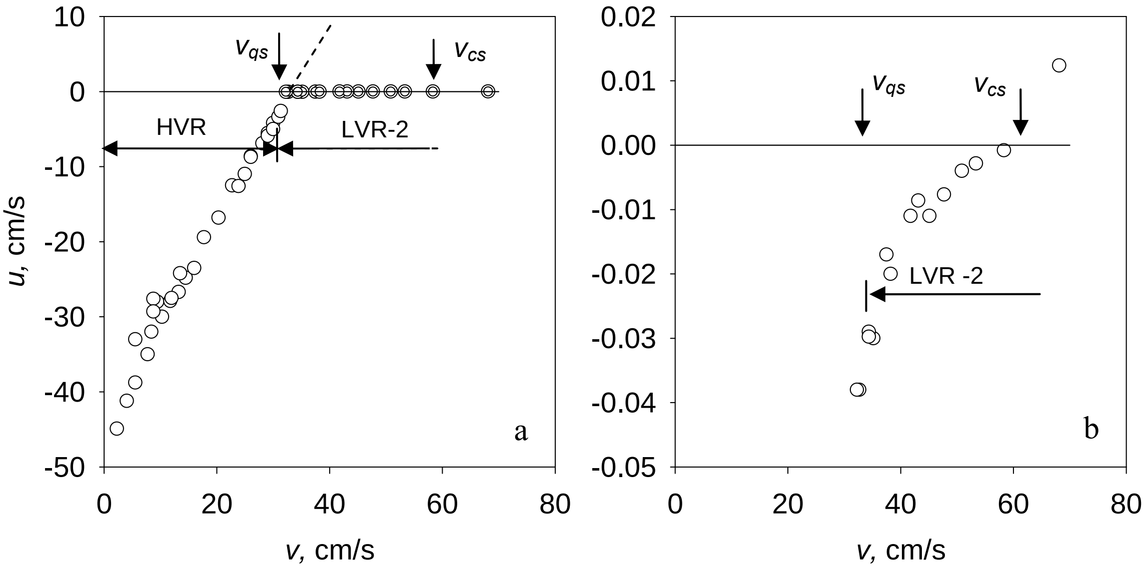

Fig.1 Transition from HVR to LVR–2 in the quartz tube d_{in}=5.1 mm, d_{out}=7.0 mm. Combustible mixture – 4% C_3H_8+air (a). The region of LVR–2 in the scaled-up (100) in ordinate (b)

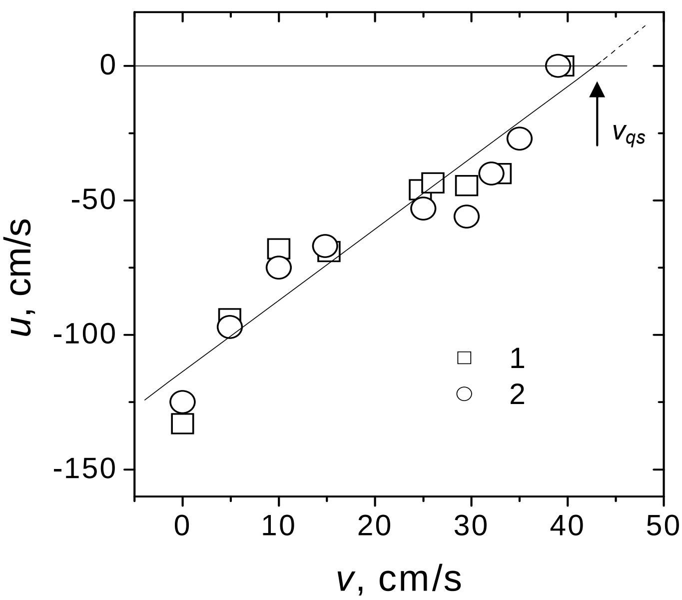

Fig.2 Dependence of combustion wave velocity in HVR on the filtration velocity. Porous medium is steel balls d_b =9.5 mm. Combustible mixtures: 1– 4% C_3H_8+air, 2 - 5% C_3H_8+air.

As examples Fig. 1 and Fig. 2 show the dependencies of steady-state velocity of combustion waves u on the counterflow velocity v in solitary quartz tube (Fig.1) and in the porous medium

(Fig. 2). It is seen that counterflow of combustible gas linearly decreases combustion wave velocity down to practically flame stopping at flow velocities near the value of laminar burning velocity (point v_{qs}). The point of v_{qs} has bifurcation properties: under rapid increase in filtration velocity the combustion wave in this point change the direction of its motion from counter to coflow (dashed line). At slow increase in the velocity the porous medium (or tube's wall) is heated in the flame zone. As result of turning on the mechanism of heat recirculation there occur increase in the burning rate and the combustion wave is slow down to the velocity values characteristic to LVR. At that there occur transition from HVR to the regime with the characteristic velocities of LVR one. The transition occurs physically continually but practically stepwise. Therefore the phenomenon near the point of v_{qs} may be called "quasystabilization" at $d>d_{cr}$, i.e. in the HVR conditions. At further increase in filtration velocity there reaches the point of labile stabilization of the combustion wave in the conditions of new low velocity regime LVR–2 (Fig. 2, point v_{cs}). Note that combustion velocity that is equal to the filtration velocity in the points of stabilization in the case of v_{cs} is in 2-3 times higher than at v_{qs}.

Table 1: Some specific features of the regimes of LVR, HVR and LVR– 2

Features	LVR	HVR	LVR–2
Region of existence on the size of porous channel, $\xi = d/d_{cr}$	$\xi<1$	$\xi>1$	$\xi>1$
Region of existence on filtration velocity v at $u<0$	$0< v\le v_{cs}$	$0\le v \le v_{qs}$	$v_{qs}\le v\le v_{cs}$
Mechanism of chemical reaction transfer	λ_{solid}	λ_{gas}	λ_{solid}, λ_{gas}
Characteristic velocity of the thermal wave, $\sigma = u/u_{LVR}$	$\sigma =1$	$\sigma >> 1$	$\sigma = O(1)$
Heat recirculation effects	+	–	+
Instability of flame of the type inflammation / extinction	+	–	+

The regime of steady-state flame propagation observed between the points v_{cs} and v_{qs} is studied in detail and classified as the LVR-2. It differs principally from LVR and HVR both the properties and mechanisms combustion wave propagation (Table. 1). As $d>d_{cr}$ then flame front width is $\delta<d$. It means that in the combustion zone there is the structure as laminar-turbulent flame one. Therefore one may expect manifestation of the effects of curvature and flame front deformation, Lewis and Karlovitz numbers effects. In the case of solitary channel the leading (stabilizing) points of flame front are near the wall in the region of minimal mixture flow velocity and maximum of gas temperature heated by wall. On front form the flame is similar to the flame of Bunzen burner. Flame front deformation and increase in its surface can result in increase in mixture combustion rate and hence to positive contribution in the heat recirculation effect. So as $d>d_{cr}$ one may also expect additional contribution in recirculation due to radiant component of the heat flux.

Other specific feature of the LVR–2 is different than in LVR reason that exclude flame flash back upstream. In the LVR conditions it is conductive flame quenching i.e. the condition of critical diameter, in LVR–2 it is gas dynamic condition $v> S_u$. As far as differences of LVR–2 from HVR are concerned in this case important features are heat recirculation and the values of velocities of thermal wave propagation (Table. 1).

During this investigation there were observed different instability of the combustion processes. In HVR in solitary channel there observed the cases of flame quenching at increase in combustible mixture velocity (gas dynamic quenching). At low flame propagation velocities there are free convection effects appearing in flame front asymmetry. In HVR there are also generated acoustic oscillations. Favourable conditions for acoustic oscillations are large diameter of the channel and the mixtures inclined to form cell flame structure. In LVR–2 in solitary channels there was found the phenomenon of oscillation combustion that manifests in periodic quenching and flame ignition in porous channels with diameter more than critical one and temperature gradient in the solid phase. Flame quenching at oscillation may be due to breaking the condition of local flame stabilization near the wall $v=S_u$, or gas dynamic flame quenching at $\tau_b=\tau_{gas}$, where $\tau_b=O(\chi/S_u^2)$, $\tau_{gas}=O(d/v)$. In the tube with d_{in}=5.1 мм with stoichiometric propane-air mixture the oscillations arise at v>43 cm/s. The measurements of sound frequency at v=45.0 and 50.8 cm/s showed that the most strong oscillations correspond the frequency of 86 Hz. Earlier similar phenomenon, but in channels with diameter less than critical one was revealed in [5, 6].

There was investigated the region of coflow flame propagation. Experiments show the possibility of implementation various scenarios of flame behavior in this region: unsteady flames in HVR and LVR-2, flame quenching, flame turbulization (chaotization), flame acceleration etc. For this region is characteristic indeterminateness of the process evolution, instability, irreproducibility of results. There are necessary additional investigations in this field.

3 Conclusion

So filtration flow in the high velocity regime influences substantially and in a number of cases determining influence on flame behavior, velocity and structural characteristics, predetermines the possibility of regime transitions, can result in instability including gas dynamic flame quenching, oscillation processes and different types of instability.

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