REGIMES OF FLUID FILTRATION COMBUSTION

N.A. KAKUTKINA
Institute of CO Chemical Kinetics and Combustion RAS, Novosibirsk

Basic physics of gas filtration combustion (GFC) is studied well enough [1]. However, there has been higher interest of the researchers to these processes [2-5]. Heat recycling process that allows to economically combust gas fuels gives particular attraction to that class of combustion processes. Many commercialized fuels are liquid under normal conditions. Therefore, attempts to combust liquids in filtration process are of interest. In [6,7] filtration combustion of hydrazine that is a liquid monopropellant was practically implemented. The objective of this work is to develop a simplified mathematical model of liquid monopropellant filtration combustion and its testing with earlier obtained experimental results on hydrazine filtration combustion.

Mathematical model

Filtration liquid combustion is considered a filtration combustion of vapors, complicated by heat abstraction to evaporate liquid. Evaporation is supposed to occur only from the surface of the liquid the temperature of which is equal to boiling point T_k. The heat from combustion products can go to liquid directly by heat conductance by gas and indirectly by solid carcass. Chemical reactions take place in vapor phase. There are no external heat losses.

At such assumptions liquid combustion wave represents two partial heat waves one of which propagates by the system carcass-liquid (zone I) and the second one – by carcass-vapor (zone II). Let a narrow zone of chemical reaction in coordinate system accompanying combustion wave be located near coordinate $x=0$ and the surface if the liquid – at $x=x_k$. Steady-state wave of filtration liquid combustion is described by a set of one-dimensional equations (1) and (2)

$$\begin{cases} \frac{d}{dx}\lambda_s\frac{d\theta_1}{dx} + c_s\rho_s u\frac{d\vartheta_1}{dx} + \frac{\alpha_1 S_c}{1-m}(T_1-\vartheta_1) = 0 \\ \frac{d}{dx}\lambda_1\frac{dT_1}{dx} - c_1\rho_1(v_1-u)\frac{dT_1}{dx} - \frac{\alpha_1 S_c(T_1-\vartheta_1)}{m} = 0 \end{cases} \quad \text{Zone I } (x<x_k) \quad (1)$$

$$\begin{cases} \frac{d}{dx}\lambda_s\frac{d\vartheta_2}{dx} + c_s\rho_s u\frac{d\vartheta_2}{dx} + \frac{\alpha_2 S_c(T_2-\vartheta_2)}{1-m} = 0 \\ \frac{d}{dx}\lambda_2\frac{dT_2}{dx} - c_2\rho_2\frac{dT_2}{dx}(v_2-u) - \frac{\alpha_2 S_c(T_2-\vartheta_2)}{m} + Q\rho_2 W = 0 \\ \rho_2\frac{d\eta}{dx}(v_2-u) + \rho_2 W = 0 \\ \rho_2(v_2-u) = G \\ \rho_2 T_2 = const \\ W = k_0\eta e^{-E/RT} \end{cases} \quad \text{Zone II } (x>x_k) \quad (2)$$

Here T and θ are fuel and carcass temperatures, η - relative concentration of fuel vapors, Q - heat effect of fuel combustion (decomposition), v - linear rate of fuel filtration, u - propagation velocity of steady-state wave of combustion relative to the carcass, ρ, c, λ - density, specific heat and heat conductivity, m - carcass porosity, α - heat transfer factor and S_c - specific surface of the carcass. Indices 1 and 2 are related to fuel in liquid and vapor phases, s - to solid carcass.

Heat wave junction at $x=x_k$ occurs according to conditions:

$$T_1 = T_2 = T_k, \quad \vartheta_1 = \vartheta_2, \quad \rho_1(v_1 - u) = \rho_2(v_2 - u) = G, \quad \eta = 1,$$

$$\frac{d\vartheta_1}{dx} = \frac{d\vartheta_2}{dx}, \quad \lambda_2 \frac{dT_2}{dx} = \lambda_1 \frac{dT_1}{dx} + \rho_1(v_1 - u)L, \qquad x = x_k \qquad (3)$$

where L is evaporation heat. Besides, the following conditions are met at the interval boundaries:

$$x = -\infty: \quad \vartheta_1 = T_1 = T_0, \quad \frac{d\vartheta_1}{dx} = \frac{dT_1}{dx} = 0,$$

$$x = \infty: \quad T_2 = \vartheta_2, \quad \eta = 0, \quad \frac{dT_2}{dx} = \frac{d\vartheta_2}{dx} = \frac{d\eta}{dx} = 0.$$

Add equations in zone I and integrate from $-\infty$ to x_k, regarding boundary conditions:

$$\lambda_2 \frac{dT_2}{dx} + \frac{1-m}{m}\lambda_s \frac{d\vartheta_2}{dx} = c_1 G(T_k - T_0) - c_s \rho_s u \frac{1-m}{m}(\vartheta_k - T_0) + GL, \qquad (4)$$

where ϑ_k is carcass temperature at $x=x_k$. Then, one can confine oneself to consideration of set (2) with boundary conditions (4) and

$$T_2 = T_k, \quad \eta = 1, \quad G = \rho_2(v_2 - u) = \rho_0(v - u),$$

where ρ_0 and v are density and rate of liquid filtration at the inlet to the system.

Having combined the first three equations of set (2) and integrated the result from x_k to ∞, we obtain a relation to equilibrium temperature:

$$\vartheta_e = T_e = T_0 + \frac{Q-L}{c_2\omega} - \frac{\Delta}{\omega}, \quad \omega = 1 - \frac{c_s\rho_s u(1-m)}{mc_2 G}, \quad \Delta = (T_k - T_0)(\frac{c_1}{c_2} - 1).$$

Then set (2) was solved by methods similar to those described in [1].

Results and discussion

As a result of the set solution, combustion wave velocity u, burnout rate $S_u=v-u$ and temperature profiles in vapor and solid phases were determined.

In general case the set has four solutions two of which correspond to two steady-state combustion regimes and the other two are unstable solutions paired with them. Fig. 1 gives calculated dependencies of combustion wave propagation velocity on filtration rate v of liquid hydrazine in quartz tubes of different inner diameter d and same wall thickness h = 1 mm. Direction from liquid phase of fuel to vapor one corresponds to positive values of wave velocity and filtration rate.

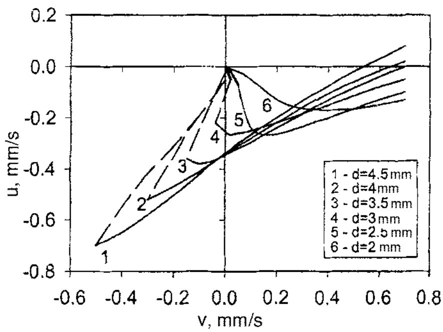

Fig. 1.Dependencies of combustion wave velocity on filtration rate of hydrazine in the tubes of different inner diameter. h = 1 *mm*

First steady-state regime is realized in the tubes of small diameter (d < 2 mm). To add, dependence $u(v)$ has V-shape typical for the low velocity regime (LVR) that is also observed at GFC in small diameter tubes. At high v one solution is revealed. Near v = 0 a second unstable solution is displayed (it is not shown in the figure due to very low values almost coinciding with v=0) that tends to stable solution at further decrease of v in v<0 (inverse filtration). v at which two solutions agree corresponds to the limit of this combustion regime.

The second steady-state regime manifests itself at relatively high values of tube diameter (d>4 mm). As in regime I, there is one solution at high v. At zero unstable solution appears (it is shown by dotted line) that agrees at lower v with stable solution in the point corresponding to the limit of the second regime. Dependencies $u(v)$ in this regime at different d have larger or smaller common interval that approximately corresponds to law $u=v-u_n$, where u_n is normal rate of liquid hydrazine combustion. Same dependence of wave velocity on filtration rate is observed at GFC in high velocity regime (HVR).

Tube diameter being 2.5-3.5 mm, four solutions appear. So, at d=3 mm and filtration rates from 0 to 0.02 mm/s hydrazine combustion can occur both in regime I and regime II. Specific realization of this or that combustion regime depends on wave initiation conditions.

Fig. 2 shows areas of existence of two combustion regimes for tubes of 1 mm thickness. Regime II is realized at $d>d_2$ in area of v to the right of curve 1, combustion being possible at $d>d_1$ only in regime II. Regime I is possible at $d<d_1$. At $d<d_2$ the area of existence of regime II ranges to the right of curve 2 (in the figure curve 2 coincides with number axis, however in reality limit values of v differ from 0 and constitute $-10^{-5}\div-10^{-3}$ mm/s). At $d_2<d<d_1$ regime I existence area is confined in v range between curves 2 and 3.

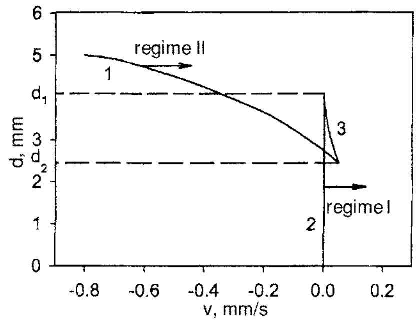

Fig. 2.Existence areas of I and II regimes

Two regimes of filtration liquid combustion are conditioned by two different mechanisms of heat transfer in the system. The first mechanism is heat conduction by gas and the second one is convective heat exchange of burning gas with the carcass with subsequent heat transfer by heat conduction by the carcass. Under regime II the major mechanism of heat transfer to heating zone is heat conduction by gas. According to wave propagation this regime is an analog to HVR at GFC. Here, however, a significant fact is that normal rate of liquid combustion is three orders of magnitude less than that for gas. This defines qualitative difference of HVR from regime II. In HVR at GFC heat bond between burning gas and the carcass is broken completely, since combustion wave in gas "runs" from the heat given by it to the carcass and this heat becomes heat losses and the carcass is heated up only by few degrees. Normal rate of liquid combustion is comparable with heat transfer rate to the carcass. Therefore, there is no complete disruption of heat bond, since chemical reaction wave does not manage to run from the heat transferred to the carcass. That is why compared to HVR, carcass under regime II is heated up quite sensibly. Heating can exceed 1000 K. Nevertheless, this heating yet accompanies chemical reaction wave, but is not an necessary criterion of its existence.

Another peculiarity of filtration liquid combustion consists in that heat transfer mechanism affects both propagation velocity of chemical reaction wave and fuel evaporation rate, i.e. process energy. Evaporation rate is defined by heat amount arriving to the surface of the liquid in a unit of time. The heat from the products to the liquid can be transferred by heat conductivity by gas and through inter-phase heat exchange by heat conduction by carcass. Here again, the effect of various mechanisms of heat transfer is different than on chemical reaction wave velocity. The effect of both heat transfer mechanisms on chemical reaction wave velocity is virtually competitive. If the reaction is driven by heat conduction by gas, chemical reaction wave loses contact with heat wave in the carcass and heat conductivity by carcass can be neglected. If the wave is driven by heat conductivity by carcass, the effect of gas heat conduction is small, since chemical reaction wave can not in any case lose contact with the carcass. Contrary to this, the effect of both heat transfer mechanisms on evaporation is additive. Heating of the carcass that can not greatly change chemical reaction wave velocity under regime II can, however, strongly alter fuel evaporation rate. This is seen well in Fig. 1. In larger diameter tubes dependence $u(v)$ follows law $u=v-u_n$ showing that combustion wave does not "notice" tube walls since burnout rate remains constant and equal to normal combustion rate. However, in smaller diameter tubes and at higher v, when heat exchange of gas with tube grows, burnout rate increases, deviating from $S_u = u_n$ due to additional evaporation of fuel owing to heat flux by the carcass.

Under regime I as in HVR at GFC, there is heat bond of gas established with the carcass and combustion wave velocity is determined by heat transfer rate by carcass. As under regime II, here evaporation rate is defined by joint effect of two heat transfer mechanisms.

Another interesting peculiarity of filtration liquid combustion (FLC) is availability of adiabatic limit by filtration rate. This limit here is called adiabatic because it manifests in the system without external heat losses. The limit is observed for both combustion regimes and always in the area of negative filtration rates. This allows to make an assumption on the limit nature. To maintain combustion, one should retain liquid fuel evaporation, i.e. its surface temperature, at a proper level. At inverse filtration heated liquid flows into the area of cold carcass and is cooled. Starting from some filtration rate, cooling exceeds critical level, fuels stops evaporating and combustion process terminates.

In tubes in which liquid combustion is possible under both regimes (d~3 mm) regime I has both lower and upper limit. The reason of the upper limit is probably a breakdown of heat bond with the carcass. Actually this is a regime transition rather than a limit. Heat exchange with the carcass in the tubes of intermediate size is relatively poor, therefore, energy growth at higher filtration rate is used to augment combustion temperature of the gas and consequently normal combustion rate. As a result, wave propagation velocity relative to the carcass that is equal to the difference of normal velocity and filtration rate increases. This leads to worse carcass heating and heat bond breakdown.

Calculations for the model were compared to experimental data for filtration combustion of hydrazine in narrow tubes [6] (Fig. 3) and porous media [7] (Fig. 4). The model for narrow tubes qualitatively correctly describes all observed regularities, namely availability of lower limit, the nature of variation of the limit and dependence $S_u(v)$ steepness at tube thickness increase. For h=0.02 mm the calculation as experiment did not reveal the limit in filtration rate range under study. Tube thickness increasing, the calculated area of flame existence narrows as an experimental one. Besides, larger tube thickness leads to sharper dependence $S_u(v)$, which is also confirmed by the experiment.

Quantitatively the calculation gives good coincidence with the experiment in the area of positive v. Deviation from experimental data is observed near the limit. Partially it can be caused by neglecting external heat losses in the model. However, the condition that at h=3.5 mm the model displays transition to regime I at v~0.1 mm/s whereas this does not take place in the experiment indicates inaccurate statement of system parameters in the model.

Data for combustion in porous media are well described by the model for regime I with switched-off heat conductivity by gas (Fig. 4). The latter is caused by the fact that the model does not take into account the screening effect of partitions located between chemical reaction zone and liquid surface and raises evaporation rate too high due to heat supply by gas. In fact this channel of heat transfer to the liquid in porous media is probably shut off. The model demonstrates correct tendency of dependence $S_u(v)$ to change when varying average pore size of porous medium and quantitatively predicts well the values of combustion rate and the limits.

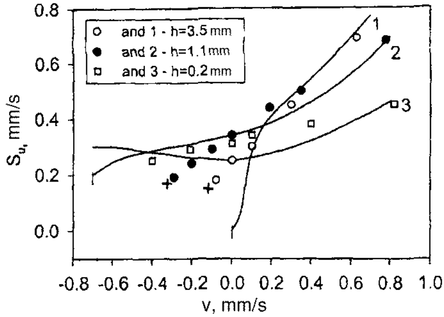

Fig. 3.Calculated (lines) and experimental (dots) dependencies of combustion rate of hydrazine on filtration rate in tubes of different thickness. d = *5mm*

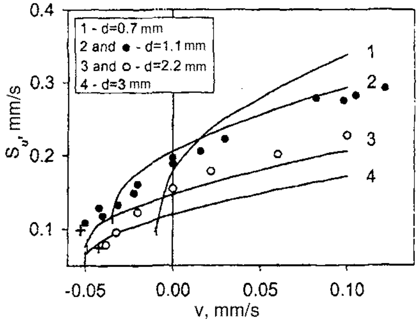

Fig. 4.Calculated (lines) and experimental (dots) dependencies of combustion rate of hydrazine on filtration rate in porous media of different dispersion. $m = 0.5$

Thus, proposed model qualitatively correctly reflects all regularities of liquid filtration combustion under study. Existence of two steady-state regimes of combustion follows from the model analysis.

Refernces.

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