COMBUSTION OF LARGE DROPLETS IN ACOUSTIC FIELD

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The present work studies experimentally the effect of flow pulsations generated by acoustic vibrations in Rijke tube on combustion of large single droplets of liquid fuels (compared to gas vibration amplitude).

As known, velocity field in the vicinity of the body placed in acoustic wave is formed by pulsation component and induced acoustic vibrations of stationary eddies - secondary acoustic flows [1].

Besides acoustic vibrations, availability of constant component of velocity of the flow running on the particle makes the situation complicated {2]. For this case velocity field both for a ball and a cylinder is not known. Experiments performed for liquid media on heat and mass transfer in pulsating flow with constant component [3] indicate complicated dependence of velocity field and transfer coefficients on vibration amplitude and frequency as well as on constant velocity value.

In gas medium secondary acoustic flow play a main role in intensifying particle-gas transfer processes. Due to their hydrodynamic influence concentration and temperature fields are formed, which affects combustion dynamics and flame shape.

Thus, experimental study of droplet combustion in pulsating flow is to reveal the influence of stationary acoustic flows on the front shape and combustion rate and can also be a necessary starting point to develop theoretical insight on the given mechanism of flow pulsation effect on combustion.

Technique of experiment

Combustion of hydrocarbon fuel droplets and magnesium was studied in a field that was a standing wave of thermoacoustic vibrations in Rijke tube. The tube is 1.1 m long and 0.1 m in diameter. Ni-Cr coil mounted at a distance of 1/4 of tube length from its bottom end was a heating element (the tube was placed vertically and open from both ends). Vibrations frequency was about 150 Hz; amplitude - more than 120 dB. In the middle of Rijke tube, i.e. in pressure variation loop, there was a hole, opening or clothing which could suppress or promote acoustic vibrations, respectively, remaining parameters of experiment not being changed.

We measured combustion time of boundary series hydrocarbon and ethyl alcohol droplets suspended on the suspension near the upper cut of the tube, i.e. in velocity variation loop. Effectiveness of acoustic influence on hydrocarbon combustion, depending on droplet size, was estimated by the time of complete fuel burn-out from porous ceramic balls of different diameter.

Besides hydrocarbons, we studied combustion of magnesium particle 3-7 mm in diameter. Magnesium ignition was performed by using separate mobile furnace; Hydrocarbons were ignited by the spark. Direct and speed schlieren-shooting and photography were made during hydrocarbon fuel burn-out from porous balls, as velocity field caused by acoustic flows in the vicinity of the particle remained unchanged.

Flame shape during large droplet combustion in acoustic field

Performed observations of liquid fuel droplet combustion in pulsating flow enable us to clearly highlight two qualitatively different types of combustion front shapes. Fig. 1

a, b

shows the first of them. Such combustion takes place at small value of constant rate component of the flow passing over the porous ball from which liquid fuel burns away. In this case hydrodynamic situation in the vicinity of the droplet is defined by the velocity field of secondary acoustic flow. Flame front looks like torus with unclosed part of the surface facing the hall. Combustion surface girdle the droplet by equatorial section (relative to acoustic velocity direction). Speedy schileren-shooting of the area above the droplet burning in the given regime indicates the availability of regularly following layers of temperature inhomogeneities which repetition frequency is equal to acoustic influence rate. Having measured the distance between the layers, we can define the velocity with which these layers are drifted along the flow. According to the picture given in Fig 1c, it is equal to 0.9 m/s.

The second type of the combustion front shape is observed at constant rate component larger than some critical value that depends on vibration amplitude (we may assume that this threshold value of constant rate component depends on acoustic vibration frequency and parameters characterizing combustion). We can consider the flow structure at given regime most clearly during magnesium combustion. Magnesium droplet is covered during reaction by oxide "jacket", which makes pattern of magnesium combustion and liquid burn-out from porous ball similar. However, the flame is not taken out from magnesium droplet at rather high flow velocities, which allows to register the flow field of the type given in Fig. 2. Here we see well three mushroom-like eddies consisting of condensed MgO, that are taken out from the combusting particle sequentially with the frequency equal to acoustic influence rate. During visual observation or at large exposure time (longer than vibration period), given flame shape is presented like a flare with corrugations. When photographing with little exposure and on speedy shooting cinegrams of hydrocarbon fuel combustion, we can observe separate lifted-off eddies of reacting vapors that follow with acoustic influence rate. At given reacting regime schlieren-shooting of hydrocarbon and magnesium droplet combustion also shows the pattern of the field of temperature inhomogeneities like lifting-off eddies having dimensions of reaction zone diameter.

Combustion rate of hydrocarbon and magnesium droplets in acoustic field

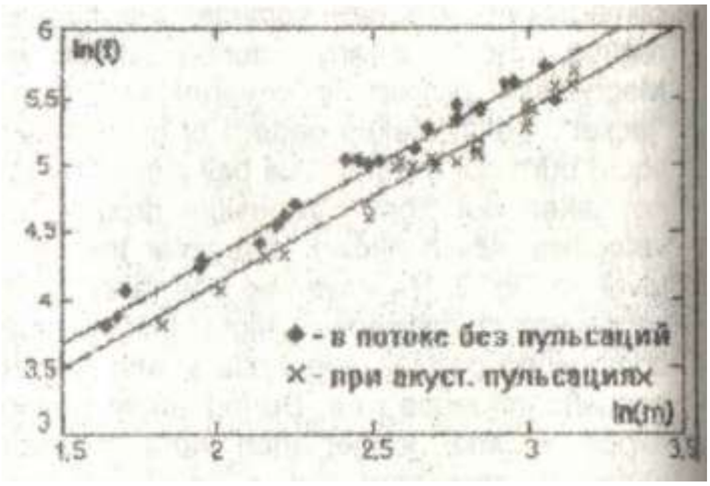
As known [4], acoustic flows intensify particle-gas heat and mass transfer processes. Acceleration of transfer processes leads to higher combustion mass rate. However, acoustic flows change the shape of heat release zone, therefore it is difficult to forecast apriori how combustion rate will change when superimposing flow pulsations.

Efficiency of acoustic vibration influence on droplet combustion can be estimated by the relative change of combustion constant k: $\varepsilon = \frac{k_a - k_0}{k_0}$, where k is calculated by measured initial droplet diameter d and its combustion time t as $k=d^2/t$. Indices 0 and a correspond to combustion without vibrations and when superimposing flow vibrations.

Measurement of relative change of hydrocarbon combustion constant was performed at acoustic influence on the droplets with initial 1.5-2 mm diameter. ε values are close for hydrocarbons of boundary series from C_5H_{12} to $C_{12}H_{26}$ as well as gasoline and ethyl alcohol and are within 0.4±0.025

To define the dependence of s on the size, porous ceramic ball of 3 to 10 mm were used that were impregnated with certain amount of substance. Time of hydrocarbon burnout from the ball was measured. It happened that ball diameter variation for hydrocarbons of boundary series did not lead to the change of ε going outside the limits of experiment error.

It is important to state that relative change of hydrocarbon vaporization rate (without combustion) that is measured similar to relative combustion rate change gives 0.12+0.01, i.e. three times less than ε during combustion. This indicates significant influence of the shape of heat release surface on droplet combustion intensification coefficient.



Results of magnesium combustion study in acoustic field are shown in Fig. 3, where dependence of spherical particle combustion time logarithm on initial mass logarithm is given. Slope coefficients of straight lines approximating experimental points are equal to n_1 =0.78, n_2 =0.77.(According to diffusion combustion model coefficient n is 2/3). Relative change of combustion time $\varepsilon_t = (t_o - t_a)/t_o$ changes from $\varepsilon_t = 0.12$ for m = 60 mg (d=4 mm) to $\varepsilon_t = 0.09$ at m=230 mg (d=6.3 mm), i.e. some growth of relative efficiency of acoustic influence with lower particle size is observed.

Conclusion

At small value of constant component of pulsating flow running on combusting droplet, combustion front is torus-like surface girdling the droplet by its equatorial section. Such shape can be explained by availability of stationary eddy flows induced by acoustic vibrations. These flows run on frontal ball parts (relative to vibration direction) and carry vapors out to middle section, consequently fuel concentration here is maximal. In the layer adjoining droplet equator secondary flows are directed from the ball surface, i.e. vapors are carried away into surrounding space where they are mixed with oxidizer. If we assume as during droplet combustion in stationary case that reaction surface coincides with the surface of stoichiometric ratio of fuel and oxidizer, it becomes qualitatively clear why combustion zone has the shape observed.

When flow constant component exceeds some critical value, combustion front shape (as well as flow field near the droplet) changes by jump-like and acquires the shape of regularly lifting-off eddies containing fuel vapors. Visually such combustion regime is presented as flare with corrugations. Similar reaction zone shape was observed at vibrational combustion of gas flare [5]. Many studies [6,7,8] of flow pulsation effect on mixing layer as well as on jets indicate that acoustic low frequency vibrations result in regular eddy formation. Given effects observed when affecting the jet with acoustic disturbance with St=0.2 - 0.6, where Strouhal number $St=f_a d/U_0$ is calculated by acoustic disturbance rate f_a and flow velocity U_o through the nozzle with diameter d. To implement the effect, some threshold excitation level [8] has to be reached. Work [3] describes the formation of regular strata during paint particle propagation in a flow of liquid with additional regular rate component. We must suppose that fuel vapor combustion observed In eddies taken from the droplet is the reflection of the flow structure at given hydrodynamic regime of passing-over.

The rate of fuel droplet combustion and combustion constant too are defined by droplet vaporization intensity and, consequently, by heat supply from combustion zone to the droplet. Higher heat flux in pulsating flow can be reached both by changing coefficients of heat and mass transfer between the particle and medium and by changing the shape and location of heat release zone, i.e. combustion front. Technique used in the present work did not allow to alter amplitude and rate of vibrations, however, we can assume that conclusion related to measured changes of combustion constant are true for sufficiently wide frequency band and vibration amplitudes.

Thus, measurements of flow pulsation effect on combustion constant indicate that:

a) relative change of combustion constant in pulsating flow differs from relative vaporization constant change, which reflects the effect of changing the geometry of heat release surface;
b) relative combustion constant changes are close for hydrocarbon of boundary series from C_5H_{12} to $C_{12}H_{26}$ and their mixture (gasoline);
c) Superimposing flow vibrations leads to the change of magnesium particle combustion rate. Relative reduction of combustion time grows with smaller particle diameter.

We can also note that changing combustion constant of hydrocarbons of boundary series does not depend on droplet diameter, however, this statement needs additional checking with wider experimental material.

Symbols

t - combustion time, d - initial droplet diameter, m - initial mass of magnesium particles, k - combustion constant, f_a - acoustic vibration rate, U_o - constant component of on-running flow velocity, St - Strouhal number, ε - relative change of combustion constant, ε_t - relative change of combustion time.

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