Droplet combustion in acoustically exciting flow.
Periodical flame-out phenomena.

V.N. Kornilov, E.N. Kondratjev
Institute of Combustion, Odessa State University,
Ukraine, Odessa 270000, Dvorynskay St. 2

The combustion of liquid fuel droplet in acoustically pulsating gas flow is a typical process for pulsing combustor or for ordinary burner under nonstationar function regime. The principal physical mechanisms of gas oscillation on droplet combustion influence depend on relation between gas displacement amplitude, frequency and characteristic spatial and temporal droplet and combustion sizes. In this paper the results of experimental researches of main mechanisms of acoustical influence on fuel droplets combustion for the cases when gas displacement amplitude *S* grater then droplet diameter *d* are presented. Influence mechanism is connected with periodical flame-out is considered.

Technique and equipment of experiment

Single magnesium and titanium small (d<S) droplets (particles) burn in the region of standing acoustical wave velocity loop - open end of Rijke tube (thermoacoustical oscillator). Rijke tube it is vertically mounted tube open on both ends with resistance element heater located at 1/4 of its length from lower end. Our Rijke tube generated acoustic vibrations with ~150 Hz frequency and 125-145 dB amplitude (*S*~0.5-1mm). In the middle of the tube, i.e. in pressure variation loop, there was a hole, opening or closing which could suppress or promote acoustic vibrations, respectively, remaining others parameters of experiment not being changed.

Granules of the metal powder were supplied to small tubular furnace placed near upper tube end. To prevent ignition of the particle inside the furnace, the latter was pumped with nitrogen. During combustion the particles are located all the time in the region of air velocity fluctuation loop, since track length (2-5 sm.) is much less than sonic wave length (2.2m).

Periodical flame-out from small magnesium particles.

Time scanning of light flux from magnesium particle burning in the flow with superimposed acoustic vibrations possesses has a number of typical peculiarities (Fig. 1). First, this is availability of sharp peaks, which repetition rate exceeds the frequency of acoustic influence two times. Alternation of deep and small dips between the peaks is the second peculiarity. It is worth highlighting the following peculiarity: high peak follows deep dip and lower peak follows small one. Light flux from the Mg particle characterizes combustion mass rate that depends on the velocity of oxidizer's flow blowing over the particle. To explain observed peculiarities of radiation flow from the particle in pulsating flow, assume that combustion mass rate dependence on on-running flow velocity for magnesium has qualitatively same shape as that of $\dot{m}(V)$ obtained for hydrocarbon fuel droplets [1]. Such dependence is schematically given in Fig.2; availability of two branches on dependence $\dot{m}(V)$ and hysteresis nature of transition between them are significant for further consideration. Combustion regime at which the flame completely embraces the droplet corresponds to upper branch. The case when the flame is taken out from frontal point and is located in the track behind the droplet corresponds to the lower one.

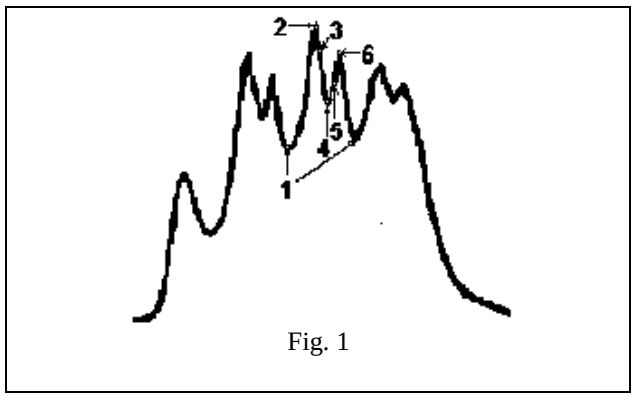

Fig. 1

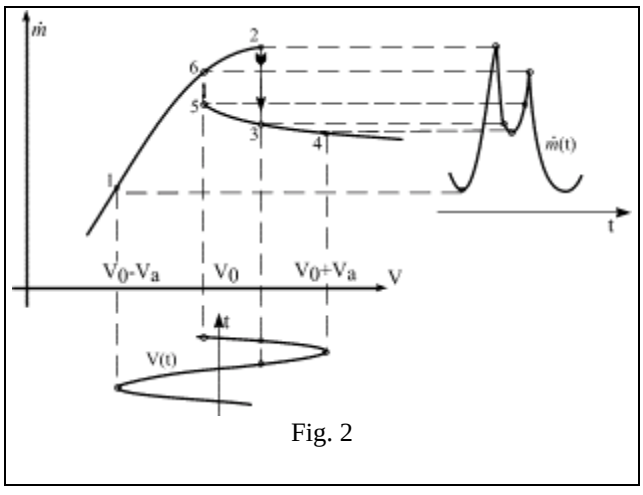

Fig. 2

Assume stationary rate of droplet blowing to be V_0. Acoustic vibration lead to the fact that blowing rate alters within $[V_0-V_a, V_0+V_a]$. Assume that combustion mass rate manages to get adjusted for current

blowing rate. Then we can easily trace scanning in time $\dot{m}$ by dependence $\dot{m}(V)$ (and that of luminous emittance, accordingly) at oscillating rate of particle blowing. Different peak height indicates the existence of hysteresis dependence $\dot{m}(V)$ for magnesium droplet and the nature of peak and dip repetition evidences that point $\dot{m}(V_0)$ is on the upper branch of combustion mass rate dependence on the velocity of the flow blowing over the droplet of given size.

Gas oscillation influence on Mg and Ti particles combustion time.

As follows from the last conclusion, during a larger portion of oscillation period combustion mass rate has instantaneous value lower than during the absence of oscillations, i.e. lower than $\dot{m}(V_0)$. This must lead to the fact that droplet combustion mass rate averaged during the period is lower than the one at averaged velocity value. The present conclusion can be verified experimentally by comparing combustion time of two similar particles in the flow with acoustic pulsation and without them. Since the particles have some variations in sizes, the difference in combustion time can be seen only performing many measurements of combustion time of different particles. The procedure of such measurements is well known [2] and was used by us.

For Mg droplet diameter 112 μm (the median of particles sizes distribution function) time of burning are 14 ms in oscillating flow and 12 ms in stationary flow. Thus, relative difference constituted -17% towards combustion time increase in pulsating flow.

At heterogeneous fuel combustion flame-out does not occur, therefore, there should be no light flux fluctuations observed from heterogeneously burning fuel particle. In fact, experiments on titanium particle combustion in acoustic field, performed similarly to experiments with magnesium, showed the absence of light flux fluctuations. Pulsation of the flow blowing over burning particle give rise to intensification of particle-gas transfer processes. If a particles burns heterogeneously in diffusion regime, combustion mass rate is defined by the oxidizer supply rate and must increase, if acoustic field is available. Using combustion of titanium particles experimentally checked the last conclusion. Within the given experiment combustion time of Ti particles 110μm decrease on ~30% in pulsating flow, compared to stationary blowing-over.

Analysis of fuel droplet flame-out in pulsating flow

Velocity at which droplet flame-out takes place decreases with lower droplet diameter. On the other hand, degree of its involvement in vibrational motion increases with lower particle size. Relative particle-gas velocity decreases accordingly. Thus, we should expect some range of particle size values at which blowing velocity amplitude exceeds the velocity at which droplet flame-out occurs. Use the bond V_{cr}, with d given in [1]:

$$V_{cr} \approx d \cdot \nu \cdot \left[\frac{B}{2 \cdot b} \cdot \left(1 + \sqrt{1 + \frac{8}{B \cdot d}} \right) \right]^2 \qquad (1)$$

here $B = U_n c_p (T_f - T_s) / (c \cdot [L + c_p (T_f - T_s)] \cdot ln[1 + \frac{c_p (T_f - T_s)}{L}])$;

$b = 2 \cdot 0{,}552 \cdot Pr^{1/3}$, (for air Pr=0,7)

thermal diffusivity a and kinematic viscosity ν are taken at $T=1/2(T_f+T_S)$; U_n - normal velocity of flame propagation by stoichiometric fuel mixture at droplet temperature.

Calculation of relative particle-gas velocity dependence on particle diameter is given in [3]. Assume that no forces, except gas resistance for, influence the particle, drag coefficient being $C=30/Re$. Then, for relative velocity amplitude we have:

$$V_a = V_g (1 + A^2)^{-1/2} \qquad (2)$$

where $$A = \frac{45}{4 \cdot \pi} \cdot \frac{\rho_g}{\rho_s} \cdot \frac{\tau \cdot \nu}{d^2}$$

here ρ_g/ρ_s-gas to droplet matter densities ratio; τ- acoustic vibration period; V_g - gas velocity vibration amplitude.

In Fig. 3 curve 1 is plotted by equation (1) and curves 2a and 2b - by equation (2) at different amplitudes V_g. (If besides vibrational component the flow blowing over the particle has some stationary portion, curves 2 will be shifted upwards on corresponding value.)

The present consideration should exclude the droplets which diameter is so small that their combustion time is less than vibrations period (curve 3 in Fig.3). Larger diameters must be limited by consideration of droplets with diameters smaller than gas shift amplitude in acoustic wave:

d< $V_g \cdot \tau/(2 \cdot \pi)$ (curve 4 in Fig.3). During larger droplet combustion additional effects related to stationary acoustic flow formation are possible.

As seen from Fig.3, blowing rate for any droplet diameter at small vibration amplitude (curve 2a) is smaller than velocity necessary for flame-out and therefore, combustion area completely embraces the droplet. When vibration amplitude exceeds some value, a range of droplet diameter values (curve 2b) appears on which $V_a > V_{cr}$. In this case during some period portion the front is taken out from frontal droplet part and fuel vapors burn in the track behind the droplet or absolutely separately from the droplet.

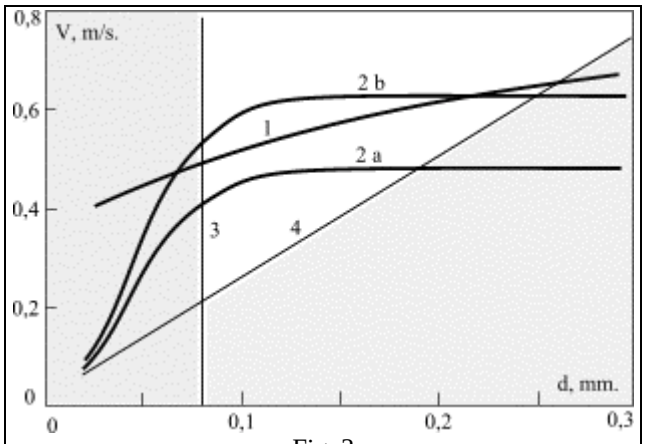

Fig. 3

What consequences can flame-out from hydrocarbon fuel droplet lead to in acoustic field? On one hand, flame-out leads to combustion time increase, as observed during magnesium particle combustion. On the other hand, gum residue combustion is speeded up, which is particularly significant during heavy hydrocarbon combustion, since in the last case gum residue combustion time constitutes major portion of droplet combustion time [4]. Again, flame-out can influence gum residue formation stage too. As known, residue is formed most intensively during pyrolysis of most heavy fuel fractions during the second half of combustion process when reaction front approaches the droplet due to which the latter is strongly heated up. Flame-out will prevent droplet overheating, hydrocarbon decomposition will be slowed down in liquid phase and, consequently, gum residue of smaller mass will remain after droplet combustion.

As well known, transparent flame is observed when burning hydrocarbon (even rather heavy) fuels in vibrational combustion chambers, i.e. soot formation is completely absent [5]. Droplet flame-out is one of possible reasons too. In fact, when the flame completely embraces the droplet, oxygen is absent in pre-flame zone from the fuel side. In this case cracking and high-temperature pyrolysis processes lead to soot particle formation. If there is even small amount of oxygen in fuel heating zone, formation of high-molecular compounds and soot is suppressed. When fuel vapors burn in the track behind the droplet or separately from it, pre-flame zone will contain some amount of oxidizer, since in this case combustion front is not closed. Thus, flame-out can be one of the reasons to reduce soot formation during hydrocarbon combustion in pulsating combustion chambers.

Briefly, the results of small particles combustion in pulsing flow investigation can be formulated as follows:

a) luminous emittance oscillogram of magnesium particle combusting in pulsating flow gives evidence about flame-out from frontal part of the droplet at some interval of vibration period;

b) flow vibrations can lead to both higher and lower average combustion mass rate value during the period, compared to combustion rate at constant blowing rate. As an outcome of lower combustion rate, time increase of magnesium particle combustion was observed in pulsating flow in our experiments;

c) during heterogeneous diffusion combustion regime, intensification of mass transfer in pulsating flow results in combustion mass rate growth, which is explained by experimentally registered time reduction in titanium particle combustion;

d) estimating rates of flame-out from hydrocarbon fuel droplet and particle blowing-over in pulsating flow indicates that droplet flame-out can take place at sufficiently high amplitude of gas vibrations in furnace volume. Fuel vapor combustion in the track behind the droplet or absolutely separately from it is one of the reasons of soot formation suppression during pulsating combustion.

References

1. V.V. Kalinchak, A.I. Struchaev, S.G. Orlovskaya, Inertial characteristics of hydrocarbon fuel flames under hysteresis. - Fizika goreniya i vzryva, 1990, 1, pp. 92-97. (in Russian)

2. M.A. Gurevich, G.V. Ignatov, E.A. Ozerov, Statistical method for metal particles combustion characteristics obtaining. - Fizika goreniya i vzryva, 1969, 3, pp. 441-444. (in Russian)

3. V.S. Severyanin, B.D. Kantselson. Some matters of vibration combustion of solid fuel. - Collected book " Vibration combustion in some model devices". Kazan, 1970. (in Russian)

4. L.V. Kulagin, S.S. Ohotnikov, Combustion of heavy liquid fuels. M.: Nedra, 1967. (in Russian)

5. Yu. L. Babkin, Pulsating combustion cameras as furnace for boilers. Teploenergetika, 1965, 9, pp. 23-28. (in Russian)