INFLUENCE OF AEROSOL, FORMED DUE TO RAPID EVAPORATION OF SUPERHEATED WATER, ON PREMIXED METHANE-AIR FLAME IN CLOSED VESSEL

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A B S T R A C T

Influence of the aerosol, formed due to rapid evaporation of superheated water with temperature 150 ^{0}C, on a premixed methane-air flame in a spherical closed vessel with a volume 20 dm^3 is experimentally investigated. Flammability limits and laminar burning velocities are determined for various water aerosol mass concentrations and gaseous mixture compositions. Low inertization effectiveness of aerosol is revealed, which is due to formation of relativly large water droplets. Aerosol inertization action is almost entirely stipulated by an availability of saturated steam in it. Exponential reduction of the laminar burning velocity of the methane-air mixtures with the elevation of a mass aerosol concentration is found.

I N T R O D U C T I O N

Aerosol formed during rapid evaporation of superheated water is widely used as an effective extinguishing tool for diffusion flames [1]. The main advantage of this tool in comparison with the traditional mechanical water dispergation is in the possibility of obtaining more disperse aerosol, extinguishing effectiveness of which is must higher. It is interesting to investigate the possibility of superheated water aerosol using not only for the diffusion flames extinguishing but for preinertization of gaseous mixtures. It is known [2-4], that water aerosol with relativaly large droplets (mean droplet diameter near 1 mm) caused not inertization but intensification of gaseous mixture combustion. In [5] it is mentioned that for the effective gaseous mixtures inertization the water droplet size must not exceed 10 μm. Though superheated water aerosol droplet size distribution isn't known it can be proposed the availibility in it of relatively small droplets which can suppress the combustion processes.

This work is aimed on the experimental investigation of the influence of an aerosol formed during rapid evaporation of superheated water on combustion of methane-air mixtures in the closed vessel. Flammability limits (FL) and laminar burning velocities S$_u$ are determined. Some experiments were executed with mixtures of ethanol vapour with air.

E X P E R I M E N T A L

Experiments were executed on the set-up "Superheating", the general scheme of it is presented in Fig.1. The reaction vessel is maid from a stainless steel and has a spherical form and volume 20 dm^3. The set-up has additionally the following elements: a pressure transducer with a time constant $3*10^{-3}$ s, an ignition source, valves for supplying of gases and superheated water, remembering ocsilloscope for the pressure transducer signal registration. The fused nichrome wire with the energy deposition 10 J placed in the center of a reaction

vessel is used as an ignition source. The superheated water was sypplied into reaction yessel from a closed heated chamber with a volume 0.3 or 1.2 dm^3 (in dependence on supplied liquid quantity). The liquid temperature was 150 ^{0}C in each experiment because water with this temperature is used for the fire extinguishing [1]. The chamber for the superheated water preparing is supplied by a thermocouple for the liquid temperature measuring and a manometer for the saturated vapour pressure measuring. This chamber is placed over the reaction vessel and connected with a reaction vessel by a valve.
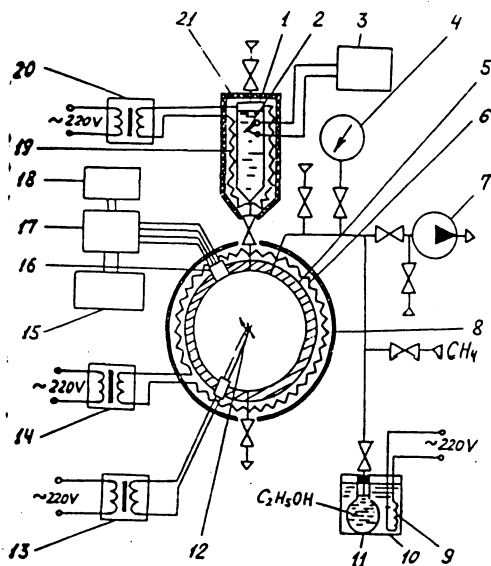

Fig. 1. The experimental set-up diagram. 1 – chamber with superheated water; 2 – thermocouple; 3 – automatic recorder; 4 – vacuum detector; 5 – reaction vessel; 6,19 – electric heater elements; 7 – vacuum pumping; 8,21 – thermal isolation; 9 – water heater; 10 – heater for ethanol vapour production; 11 – vessel with ethanol; 12 – ignition source; 13,14,20 – transformers; 15 – osciloscope; 16 – pressure transducer; 17 – amplifier; 18 – source of direct current.

Experiments were executed by a following manner. For a superheated water preparing the required quantity of liquid is placed into a chamber at a room temperature. Then this chamber was seated hermetically and heated up to a required temperature. The combustible gaseous mixture was prepared by a partial pressure in a preliminary evacuated to a residual pressure 0.1 kPa reaction vessel with an exposure non less than 30 min for an appropriate mixing. Then a heated chamber was connected for a short time with a reaction vessel, and as a result some quantity of a superheated water is introduced into it and evaporates rapidly with a gas-aerosol mixture formation. After some time the ignition source was initiated.

Pressure in reaction vessel was detected during the whole experiment from a superheated water introducing begining to a

cooling of combustion products. It was accepted that the flame propagates in a gaseous mixture, if a pressure increase in the reaction vessel after the combustion initiation exceeds 30 kPa. The initial absolut pressure was 100-150 kPa, maximum explosion pressure 400-900 kPa (depending on a mixture composition, ignition time delay and quantity of supplied superheated water). The choice of a limiting pressure value for a flame propagation detection (30 kPa) is some conventional and characterised the near-limit combustion regime with a low combustion completeness. The pressure increase at ignition source in non-combustible mixture (for example, in air) is sufficiently lower than menthioned above limiting value.

Flammability limit value was determined as a mean of two concentrations, at a first one of which it was not less than three mixture ignitions and at a second-not less than three non-ignitions [6]. The quantity of a superheated liqiud introduced into a reaction vessel was determined as a difference between the initial water mass in a heated chamber and a water mass remaining after an experiment in this chamber.

Laminar burning velocity was determined by a method proposed in [7] and developed then in the standard [6]. The essence of this method is the following. Numerical modelling of a flame propagation in a closed spherical vessel at a central ignition is made by a method [8]. The dependence of a laminar burning velocity S_u on a non-dimensional pressure π during the adiabatic explosion is described by a formula

$$S_u = S_{ui} \pi^\varepsilon ,$$

where S_{ui} – laminar burning velocity at initial pressure and temperature; ε – generalized thermokinetic index for the gaseous mixture.

By means of the repeated numerical integration of equations describing combustion of a gaseous mixture in a closed spherical vessel the optimum S_u and ε values are determined which give the best agreement between calculated and experimentally measured pressure-time hystories on a pressure-time curve from a pressure 0.1 P_{max} (P_{max} –maximum explosion pressure) to a value P_*, which is determined by a condition $d^2 P/d\tau^2 = 0$.

The relative error of the laminar burning velocity determination doesn't exceed 20 %, for another measured parameters – 10 %.

R E S U L T S   A N D   D I S C U S S I O N

The typical pressure-time curves for the superheated water introducing, the steam condensation and after the combustion initiation are presented in Fig.2. The first maximum on a curve in Fig.2a corresponds to a time moment of superheated water introducing finishing. The pressure increase till this time moment is caused by a superheated water evaporation and steam formation, and the pressure deacrease after this time moment is caused by a steam condensation. The part of the pressure time curve in Fig. 2a till the combustion initiation moment shows a time change of steam partial

pressure. After a time interval of 10 s a pressure returns to its initial value. After a time interval of 5 s (at the mixture ignition time moment) a pressure rise ΔP in the reaction vessel is near 40 kPa. The ΔP value at the mixture ignition time moment was monitored in each experiment. The mixture temperature at this moment was 60-80 $^\circ$C. The total pressure-time curve during the experiment (Fig. 2b) is characterised by two parts: from a superheated water introducing begining to a mixture ignition (the character of this part of the curve was qualitatively discussed earlier) and from a mixture ignition to a combustion finishing. This part is typical to a gaseous mixture combustion in a closed vessel and was used by us for a laminar burning velocity determination.
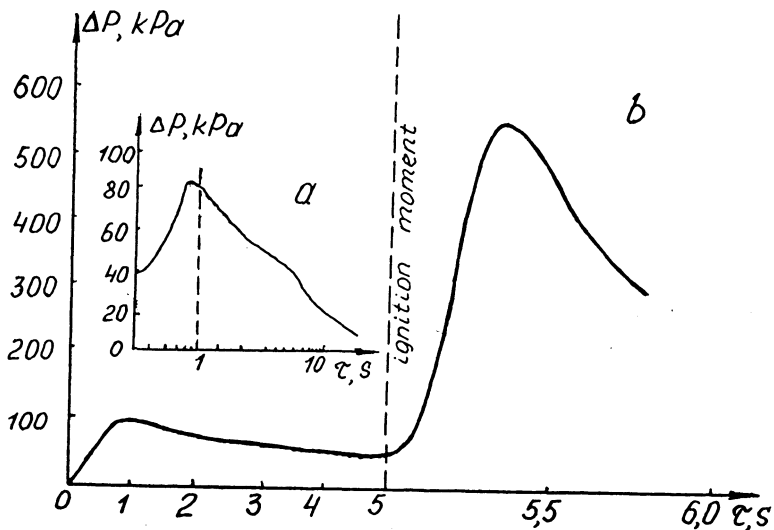

Fig. 2. The dependence of a pressure in the reaction vessel on a time at the superheated water supplying (partial steam pressure) (a) and at combustion initiation (b). Methane concentration 9,5 % (vol.). Water aerosol mass concentration 22 g/l. After an ignition time moment a time scale change on a diagram (b) takes place.

In Fig. 3 the dependence of methane flammability limits in air on the water aerosol mass concentration is presented. For the comparison the analogous dependence of methane flammability limits in air on steam concentration is shown [9]. The mixture composition at the extremum point of the curve is close to stoichiometric one, and the superheated water aerosol mass concentration in this point is equal 29.5 g/l. For the stoichiometric mixture of the ethanol vapour with air at the initial temperature 40 $^\circ$C (preliminary reaction

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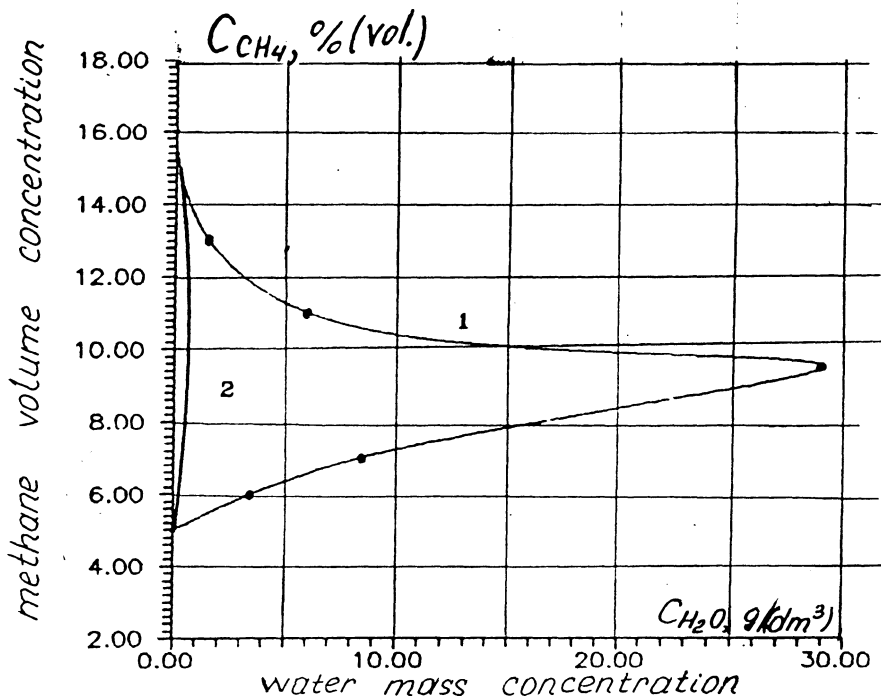vessel heating) this concentration is equal 32 g/l.

Fig. 3. The dependence of flammability limits for methane-air mixture on water aerosol mass concentration (1) and steam (2) (data from [9]).

From Fig. 3 we can see that the mass inertization concentrations in relation to the stoichiometric methane-air and ethanol-air mixtures are much higher for superheated water aerosol than for steam. This effect is probably due to formation in the reaction vessel volume relatively large water droplets, which characteristic sizes are near 40-50 μm [1]. These large droplets have not sufficient time to evaporate in a narrow flame front and therefore don't influence significantly on the combustion process. It can be proposed that the superheated water aerosol inertization effectiveness is due to steam formed during the superheated water evaporation. This proposition is confirmed by data presented in Fig. 4, where methane-air flammability limits with steam are shown. The solid curve - experimental data from [9]. The experimental points - the data of this work, recalculated by means of partial steam pressures detected at the ignition moment (only steam mass concetration is taken into account). The satisfactory agreement of our experimental data with results [9] is observed, and this fact confirms our proposition about the main role of steam in methane-air mixture combustion inertization. This proposition is demonstrated also by the another effect that is an aerosol mass inertization concentration increases with the increase of
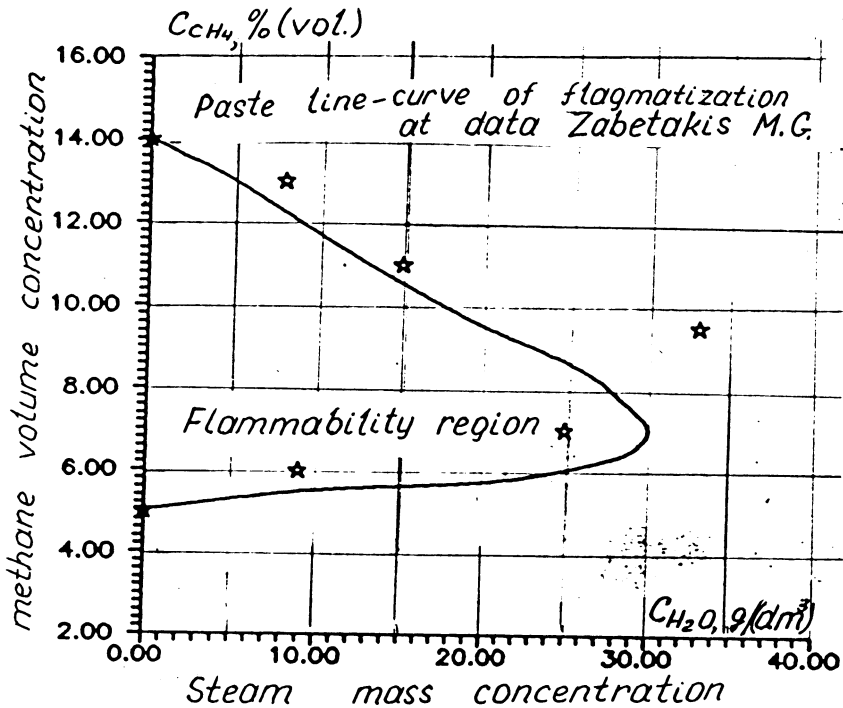
a time delay of a mixture ignition.

Fig. 4.   The dependence of flammability   limits   for
         methane-air mixture C_{CH_4} on steam concentration
         C_{H_2O}. —————— - data from [9]; ★ - data of this
         work.

The low   water aerosol inertization effectiveness in
comparison with steam is caused, as pointed above,   by
relatively large water droplets formation, which don't have
sufficient time to evaporate in a narrow flame   front.   These
relatively large water droplets don't play a significant   role
in a diffusion flame extinguishing (for example, in the case
of liquid pool flames), because even large water droplets have
sufficient time   to evaporate in a flame (including preheated
flame zone and combustion products) which had a large size in
comparison with a narrow front of premixed flames (droplet
evaporation in combustion products of premixed flames doesn't
influence   sufficiently on flame propagation). This fact
explains the difference of the superheated water aerosol in
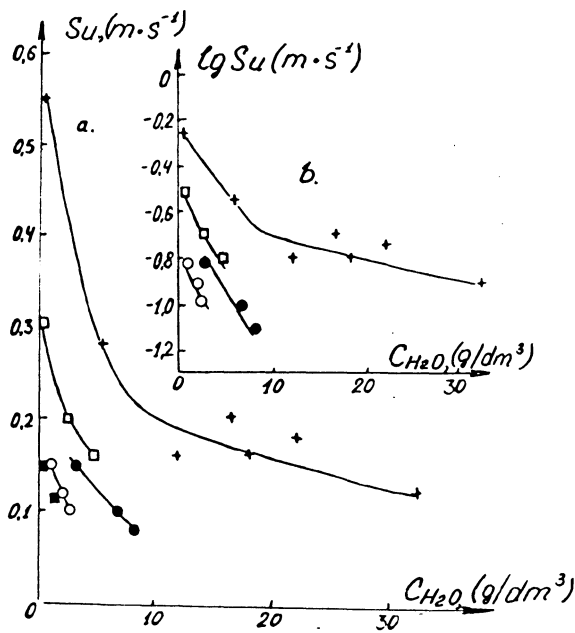relation with premixed and diffusion flames.

Fig. 5. The dependence of laminar burning velocity S_u of methane-air mixture on water aerosol mass concentration C_{H_2O}. C_{CH_4} = 6(■), 7(●), 9.5 (+), 11(□), 13(○) %(vol.).

In Fig. 5 the dependence of laminar burning velocity S_u for methane-air mixtures on superheated water aerosol mass concentration C_{H_2O} is presented. A rapid S_u deacreasing with C_{H_2O} elevation, which has an exponential character, takes place. In [10] the analogous character for the dependence of a laminar burning velocity of hydrogen-air mixtures on steam concentration is revealed. Qualitatively the same dependence takes place in Fig.5b at low superheated water aerosol mass concentration. At more high C_{H_2O} values the laminar burning velocity S_u of stoichiometric methane-air mixtures changes more slowly, and this fact is probably caused by a reduction of superheated water mass part which produces steam.

It must be noted that both during a superheated water supplying and after it till the ignition moment some part of water is settled on reaction vessel walls, and it is very difficult to evaluate this part in a set-up used in the work. The account of water settling will change some features of presented dependencies, but the conclusion about the main role of steam in inertization effectiveness will remain invariable.

CONCLUSIONS

1. The influence of an aerosol formed during rapid evaporation of superheated water on combustion of premixed methane-air mixtures in closed vessel is experimentally investigated.

2. The dependencies of flammability limits and laminar burning velocities on a superheated water aerosol mass concentrations are determined.

3. The low inertization effectiveness of superheated water aerosol is revealed, which is caused by a large water droplet formation. The inertization effectiveness of such aerosol is due to the presense of steam in it.

4. The exponential reduction of a laminar burning

velocity of methane-air mixtures with an aerosol mass concentration increase is shown.

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