Investigation of hydrogen-oxygen mixture combustion in the flow of steam

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1 Introduction

At present influence of water vapor flow on combustion of hydrogen and oxygen mixture remains underinvestigated; further more there is no complete physical model that would serve to predict the behavior of hydrogen, oxygen and water vapor mixture within the wide range of parameters. One of the possible phenomena at hydrogen combustion in water vapor medium is changing dimensions of combustion torch both for the account of the decreased inflow of the oxidizer to the flame torch and cooling of periphery flame areas by vapor flow as well as for the account of intense mixing of high-temperature water vapor resulting from combustion with the supplied water vapor. Finally we face an interesting situation when the product of full combustion of hydrogen and oxygen mixture turns out to be high-enthalpy water vapor interacting with the supplied low-enthalpy water vapor.

This paper presents main results of experimental investigations and calculation modeling of hydrogen and oxygen mixture combustion in water-vapor flow at high water vapor concentrations.

2 Experimental setup

To investigate experimentally hydrogen-oxygen mixture combustion in the steam medium, the laboratory setup, whose scheme is shown in Fig. 1, was developed and made. The main units of this laboratory setup are as follows: electrolytic section for hydrogen-oxygen mixture production; steam generator; working section, where mixture burns; steam condenser; and unit for flow rate measurements of steam and noncondensable gases. Saturated steam with the temperature of 100ºC and stoichiometric hydrogen-oxygen mixture with the temperature of 20ºC are fed simultaneously into the working section. The working section is a hollow quartz-glass cylinder; the combustible mixture is supplied along the axis of this cylinder, and steam is fed at its periphery. In experiments the sizes of the working section were changed: its diameter was 10, 14, and 20 mm, and the length varied from 100 to 200 mm. The diameter of nozzle for combustible mixture supply was 0.5 mm. The flow rate of steam, fed into the burner, was changed from 200 l/min to the minimal flow, determined only by the measurement accuracy: 30 – 35 l/min. The flow rate of combustible mixture was determined by productivity of electrolytic section; its minimal value in the experiments was 3.4 l/min.

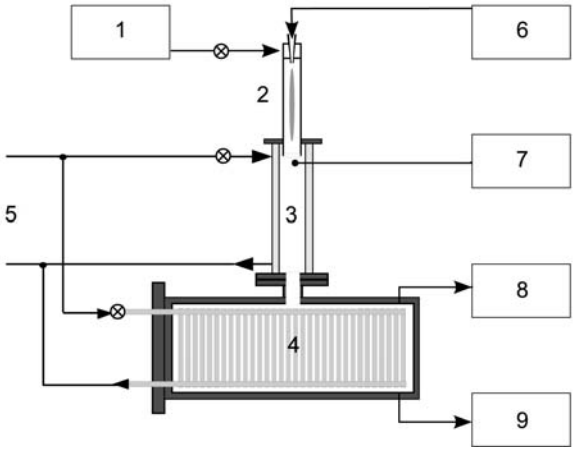

Figure 1. The scheme of experimental setup. 1- system of steam supply, 2- working section, 3 - condenser, 4- condenser-separator, 5- cold water main, 6 – system for combustible mixture generation, preparation and fire protection, 7- system of temperature measurements, 8- system for registration of unburned gas flow rate, 9- systems for registration of condensate flow rate.

To study combustion completeness of hydrogen-oxygen mixture in the steam medium, the system for collection of combustion and mixing products with simultaneous measurement of steam and noncondensable gas flow rates was made. For this purpose the known principle of steam condensation in a liquid volume was used.

3 Experimental results

The pictures of flame, formed at combustion of stoichiometric hydrogen-oxygen mixture without (a) and with (b) steam flow, are shown in Fig. 2. The flow of saturated steam with the temperature of 100ºC from the working section (in this case only steam is fed to the working section inlet) (c) and the outflow of reaction products of hydrogen-oxygen mixture combustion in the steam medium (d) are shown in Fig. 2 also. The effect of steam flow on the visible length of the flame at combustion of hydrogen-oxygen mixture was detected. An increase in steam flow rate reduced significantly the flame length; with the following increase in steam flow rate the flame-out and flame quenching were observed. Flame shortening reduces significantly the zone of heat transfer between the combustion products and steam.

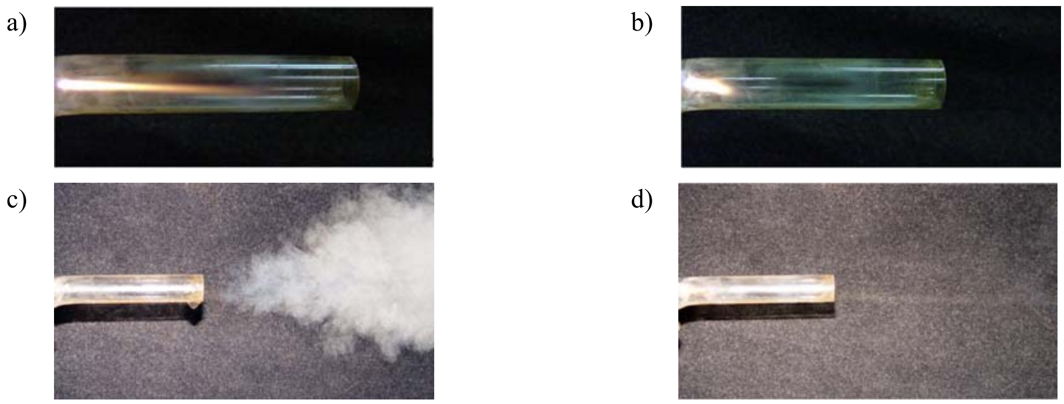

Figure 2. The photo of flames – a), b) and steam out c), d).

Experimental data on the effect of combustible mixture portion in the initial steam flow on completeness of hydrogen-oxygen mixture combustion, determined by the amount of noncondensable gases, are shown in Fig. 3b. According to the diagram, there is clear reduction in the portion of uncondensable gases at a rise of the portion of combustible mixture in steam. With a rise of this value from 2 up to 30 %, the portion of unburned gas mixture decreases from 8 -10 % to 2 %. A change in the working section sizes slightly effected a change in the portion of uncondensable gas.

Dependence of temperature of high-enthalpy steam on the portion of hydrogen-oxygen mixture in the initial steam flow is shown in Fig. 3a. It follows from the diagram that with a rise of the portion of combustible mixture, the temperature of produced steam increases and reaches the values of about 1000ºC at combustible mixture concentration of 20 – 30%.

The studies of combustion conditions have shown that at low relative concentration of combustible mixture spontaneous flame-out and termination of hydrogen-oxygen mixture combustion can occur. This phenomenon is connected with perturbation of the steam flow, coming into the burner.

4 Numerical modeling

Equation system of mathematical model describing combustion of stoichiometric mixture of hydrogen and oxygen included equations of continuity, impulse and energy, mass concentration of the components and standard $k-\varepsilon$ model of turbulence. To model stationary turbulent combustion the model of vortices dissipation ED (Eddy Dissipation) [1,2] and generalized model of vortices dissipation EDC (Eddy Dissipation Concenpt) [3,4] were applied. Physical essence of ED model is as follows. Rates of chemical reactions are supposed to be very high and within the time scale of turbulent mixing of reagents maximum yield of reaction products depends on minimum concentration of initial reagent. EDC model implies that at turbulent mixing mixture combustion occurs in small-scale turbulent vortices. Volume fraction of these vortices in the grid cell is determined according to the formula $\xi^* = C_\xi \left(\nu\varepsilon/k^2\right)^{3/4}$, where k is energy of turbulence, ε - dissipation rate k, ν - kinematic viscosity, and C_ξ =2.1377 – empirical constant. Reaction in these volumes occurs within the period of turbulent mixing $\tau^* = C_\tau \sqrt{\nu/\varepsilon}$, and C_τ =0.4082 – empirical constant. Reaction systems for hydrogen and oxygen combustion kinetics considering formation of interim radicals contain tens of reactions. In the calculations simplified model of "global reaction" H_2 + 0.5 O_2 = H_2O was used, where velocity was calculated according to Arrhenius formula with pre-exponential factor 9.78 10^8 $m^3kgmol^{-1}s^{-1}$ and activation energy 3.1 10^7 J/kgmol. To take into account possible dissociation of the formed molecules of water calculations backward

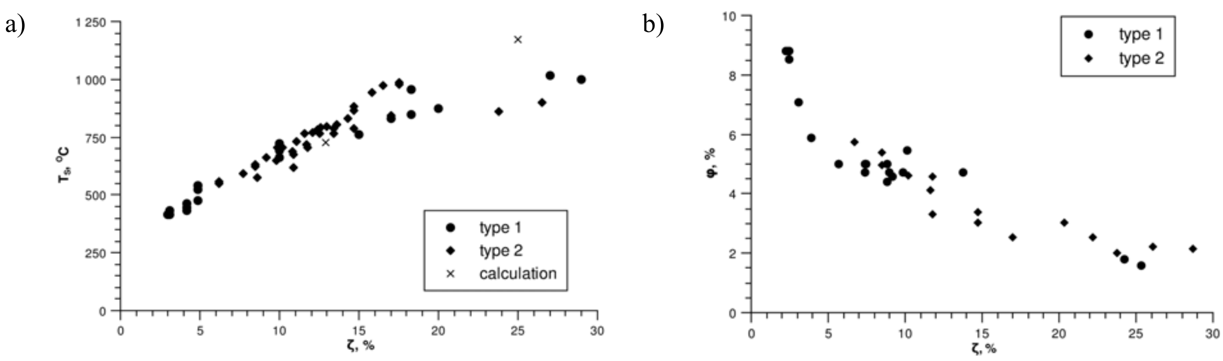

Figure 3. Outlet steam temperature – a) and ratio of unburned fuel flow rate to supplied fuel rate –b) vs ratio of supplied fuel flow rate to total flow rate.

reaction was taken into account, its rate was calculated with the standard method. Thermophysical properties of the components were calculated with polynomial approximations and mixture properties were determined in the multicomponent ideal gas approximation. Solving the model equation system at each iteration we numerically integrated equations of chemical kinetics within the mixing time (range) scale τ^*.

For the model approbation combustion of stoichiometric mixture of hydrogen and oxygen was calculated in two-dimensional statement for experimental conditions. Results of temperature calculation are presented in the Fig 4a. It is apparent that ED model noticeably exceeds temperature maximum compare with the maximum of 3073 K at adiabatic combustion of stoichiometric mixture of hydrogen and oxygen. At the same parameters kinetics consideration in EDC model under adiabatic conditions gives maximum 2700 K, typical for hydrogen flame. Consideration of heat transfer with ambient medium results in the temperature decrease however the value of temperature maximum practically does not change. Calculation using EDC model of steam overheating for range steam flow rate 0– 2.2 g/s were performed at pressures 1 atm and 30 atm. Comparision of measured and calculated temperature of overheated steam are presented at Fig. 3a. At pressure 1 atm results of calculation fairly accords with experimental data. Temperature filed in steam overheater model are presented at Fig.4b.

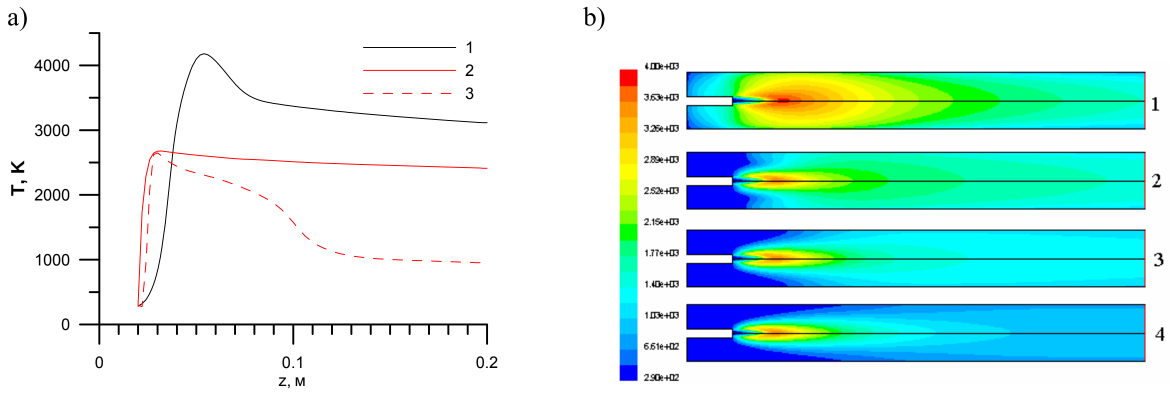

Figure 4. a)- Axial steam temperature profile: 1 – ED model, 2 – EDC model, 3 – EDC model with account for heat transfer to environment. b) - Temperature filed in steam overheater vs different of supplied fuel flow rate.

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