Temperature measurements on the surface of a sampling probe in a flame

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Abstract. The probe sampling of gases is extensively used in studies of high-temperature oxidation processes. This technique allows one to obtain directly information on the chemical composition of the reaction volume, however, inevitably introduces thermal and gas-dynamic perturbations into the system. In order to further numerically simulate the sampling process, the temperature profiles of the quartz probe surface in the CH₄/O₂/Ar flames were measured in a pressure range of 1-5 atm. The measurements were carried out by thermographic method using an IR camera, which was calibrated by direct thermocouple measurements taking into account flame shielding. The data obtained will be used as boundary conditions for computer simulation of the sampling processes, which will significantly improve the accuracy of the sampling probe methods.

1. Introduction

Sampling probes are often used to extract gas sample from the flame. Typically, the sampling probe is a quartz or metal cone several centimeters height with a hole on its tip. The hole diameter varies from 20 to 500 μm depending on working pressure and pumping system performance. The opening angle of the cone varies typically from 10° to 90° defining the sampling regime: leakage (<40° conditionally) or molecular beam mode (≥40°). On the one hand, molecular-beam sampling experiments are more useful to get insight into combustion chemistry, because they enable the flame radicals to be detected. On the other hand, more obtuse probe represents a physical barrier for gas flow and introduces significant thermal perturbations. In addition, chemical reactions can occur on the probe surface, particularly, recombination of radicals [1-3]. These disturbances lead to distortions of the temperature and mole fraction profiles in the flame front (flame structure), and thus cause a systematic measurement errors, which are difficult to eliminate.

The only way to take into account the probe perturbations is a full computer modeling. A comprehensive numerical simulations and analysis of the probe perturbations at atmospheric pressure were carried out earlier [4, 5]. Deng et al. [5] developed a computer model, which was used in combination with a detailed chemical kinetic mechanism for methane combustion. This made it possible to show accurately the effect of the probe on the mole fraction profiles of species in the flame front. The approach proposed by the authors appeared to be an effective method for taking into account the probe perturbations. However, the model requires further development and verification.
For correct calculations large computing powers are required, but they could be reduced adding experimentally measured parameters to the model. One of these parameters is the probe surface temperature. It is determined by the balance of heat fluxes: from the flame to the probe and from the probe to the cooled flange. Such temperature profile characterizes the actual setup. Thus, the purpose of the work was to measure experimentally the temperature distribution on the probe surface in the flame front at conditions corresponding to [5]. Additional interest was associated with pressure influence on temperature gradient on the probe surface.

2. Experimental details
The probe studied was a sampling probe of a molecular-beam mass-spectrometer (MBMS) setup in ICKC [6,7]. The probe was a quartz cone 15.2 mm height with a hole on the tip. The hole diameter was 120 \( \mu \)m, the wall thickness was 140 \( \mu \)m at the tip and thickened to 270 \( \mu \)m at the base. The internal angle of the cone was 40°. The probe was attached to a cooled flange, temperature of cooling water was 18-20 °C.

The surface temperature of the probe was measured in premixed flames stabilized on a flat burner. The measurements were carried out in lean methane flame at atmospheric pressure and stoichiometric methane flame at pressures of 1, 3 and 5 atm. To stabilize the flame at atmospheric pressure the flat Botha-Spalding burner with diameter of 16 mm was used. For experiments at elevated pressures the flat burner of 6 mm diameter was also used [7]. Characteristics of the lean flame CH\(_4\)/O\(_2\)/Ar (0.06/0.15/0.79 in mole fractions, flow rate 25 cm\(^3\)/s, \( \varphi = 0.8 \)) were taken in the same way as in [4, 5]. Compositions of stoichiometric flames at atmospheric and elevated pressures as well as stabilization conditions were taken from [7]. For these flames the CH\(_4\)/O\(_2\)/Ar mixture was mixed in proportions 0.0833/0.1667/0.75, the total flow rate was 50 cm\(^3\)/s for atmospheric pressure and 22 cm\(^3\)/s for 3 and 5 atm. The measurements at elevated pressures were carried out in a high-pressure chamber, also described in [7]. The chamber was developed to operate at pressures up to 10 atm. The burner was fixed in a brass housing, which was attached to the bottom of the chamber by threaded connection. The chamber was equipped with a sight window (optical quartz glass) for optic access and a manipulator for thermocouple positioning inside the chamber. Fully assembled high-pressure chamber was mounted to the cooled flange of the MBMS setup. The chamber was pressurized with nitrogen, a diaphragm pressure regulator on the exhaust line was used for pressure control.

Since micro-thermocouple measurements of the surface at each point are rather time-consuming (especially in a high-pressure chamber), it was decided to use an optical method to obtain instantaneous pictures of the temperature distribution on the probe. The surface temperature of the probe was measured using an IR camera JADE 1530SB with a resolution of 320 \( \times \) 240. Measurements at 1 atm were done in 3.7-3.9 \( \mu \)m spectral range where the flame is almost transparent. At elevated pressures (3 and 5 atm) a filter with the spectral interval of 2.5-2.7 \( \mu \)m was chosen due to optical properties of the sight window. Thermographic camera was calibrated on the AChT-45/100/1100 which simulates emission of an absolutely black body. Since the flames were screened by the sight window at high pressure regimes, an additional calibration of the glass was carried out.
Reference micro-thermocouple measurements were done in several points on the probe surface. Thin Pt/Pt-Rh (10%) thermocouples coated with a SiO$_2$ were used. The wire thickness was 30 $\mu$m, the total thickness of coated thermocouples was 60±15 $\mu$m. To measure the temperature of the perturbed flame, the thermocouple was placed under the probe at the burner axis in the burner plane (figure 1, position 1) and at some distance from the axis of the burner in the same plane. The probe surface was measured at the probe tip (position 2) and on the probe wall (position 3) above the hole. In the flames at 3 and 5 atm only the wall temperature (position 3) was measured. To measure the probe surface temperature, the reference thermocouple was stretched onto the probe wrapping it around the outer surface of the cone. Thus a good thermal contact between the surface and the thermocouple along the entire length of the thermocouple arms was provided. Thermocouple and the burner position relative to the probe were controlled by a cathetometer with an accuracy of ±20 $\mu$m. Measurements in each point were carried out at least two times.

3. Results

As a result, numerical data on the temperature distribution on the probe surface were obtained. Temperature measurements were carried out at different distances between the burner and the probe $h$; typical IR images of the probe are shown on figure 2.

Analysis of temperature profiles at each point along the surface of the probe (along line from the tip to the base) showed that at atmospheric pressure the temperature profile on the surface is similar to the temperature profile in the flame (figure 3 (left)). At pressure of 3 atm, the temperature profile at the surface corresponds to the tail of the temperature profile of the flame, and the temperature of each point of the surface changes insignificantly from $h$ (figure 3 (right)). This fact indicates that the flame zone under these conditions is very narrow and for any $h$ the probe is in the final flame zone. Experiments at 5 atm exhibited the same tendency.

It is worthy of note that calculated adiabatic temperature of stoichiometric flame at 1 atm reaches 2440 K, at 3 atm it is 2488 K and at 5 atm it augments up to 2510 K. But since the flames are stabilized on the burner, the adiabatic temperature is not reached, even without the probe. Thus for correct simulations we always have to measure real temperature profiles in flames.

4. Discussion and conclusion

Temperature distributions on the surface of the quartz probe of MBMS-setup were measured in premixed methane flames using thermographic measurements in combination with reference micro-thermocouple measurements. The flames were stabilized on a flat burner at pressures 1, 3 and 5 atm. The temperature fields were measured by an IR camera. To estimate effective emissivity of the probe in flame, reference measurements were done by thin thermocouple on the surface of the probe. Probe shielding by the flame and a sight window was taken into account. Temperature distributions on the
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probe surface were analyzed as a function of distance between the burner and the probe \( h \) for different flames and pressures.

Analysis of temperature profiles at each point of the surface along the probe axis revealed that at atmospheric pressure the temperature profile on the surface is similar to the extended temperature profile in the flame. This corresponds to the supply of heat through the probe to preheating zone of the flame. At pressures of 3 and 5 atm temperature profiles on the wall corresponds to the temperature distribution in the postflame zone. Temperature in each point of the probe surface varies slightly from the distance \( h \). This fact indicates that the flame zone under these conditions is very narrow and for any \( h \) the probe is in the final flame zone. Such influence of the probe distorts minimally temperature gradient in the reaction zone of the flame. Low gradient perturbations ultimately simplify comparison of experimental data on flame structure with chemical-kinetic simulations. Unfortunately, at atmospheric pressure the gradient distortion is high enough and we have to take it into account. The results obtained will be used to develop and test the probe perturbation models.

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Figure 3. Temperature profiles along the probe surface in stoichiometric flames at 1 atm (left) and 3 atm (right). Each curve corresponds to one experiment; numbers correspond to the position (in mm) of the tip relative to the burner.