Experimental Study of Single Wall Flame Quenching at High Pressures

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1 Introduction

It is well known that in vicinity of wall, the thermal heat losses become large enough to slow down chemical reactions, to stop flame propagation and to quench the flame. When the flame reaches the wall, the wall heat flux strongly increases. At the instant of the flame quenching, the wall heat flux gets its maximum. The heat losses during flame quenching must be taken into account for energetic optimization of ignition and combustion devices [1]. The development of internal combustion (IC) engines loop control requires data compatible with non-stationary, single-shot combustion. These data cannot be predicted by stationary correlations, as previously demonstrated in [2,3]. The implementation of new combustion technologies, such as Homogeneous Charge Compression Ignition (HCCI) or high pressure combustion (HPC), is directly related to the detailed information on the heat exchange processes during the wall flame quenching at elevated pressures. The experimental difficulties of the flame quenching study are marked in [2,3]. These difficulties just explain the lack of data for a high pressure range (higher than 1MPa). Therefore new experimental data characterizing the single wall flame quenching at high pressures are required.

Previous works showed that ion current [4,5] and wall heat flux [2,3] diagnostics allow an estimation of flame quenching distance. The results were validated for a pressure range of 0.08-0.35MPa. In this paper we used these diagnostics in an extended pressure range of 0.05-16MPa. The results of this experimental study are also discussed. We analysed pressure evolutions of the maximal wall heat flux density Q_w and the quenching distance δ_q (i.e. minimal distance at which flame approaches the wall during the quenching).

2 Experimental

Wall heat flux experiments were carried out in the combustion chamber of a Rapid Compression Machines (RCM) described in [6]. In the RCM, horizontal movement of the guiding rode is transformed in the vertical motion of the compressing piston in the cylinder of square cross-section $50x50mm^2$. The combustion chamber is mounted at the end of cylinder. The chamber volume is well stabilized at top dead position of the piston which is blocked after gas compression phase. The volume of RCM combustion chamber was equal to $50x50x30mm^3$. The total time of compression is about

38ms. The compression ratio was set to ε=13. Flat windows are mounted on lateral sides of RCM chamber, enabling visualization of combustion in the whole chamber's volume.

A stoichiometric quiescent methane/air mixture was ignited by a spark plug. In all tests the igniting electrodes were placed at the centre of the combustion chamber. In tests the ignition occurred with a delay of about 80ms after the end of the compression. After this delay, a slow residual gas motion is obtained. It allows a laminar combustion regime [6] observed by direct visualization. Obtained snapshots of the flame front showed that head-on type flame/wall interaction occurred. Ignition point was placed at the symmetry axis of a heat flux gauge of CFTM type flush mounted with the chamber wall. Thus the regime of head-on flame quenching was studied thanks to this geometrical arrangement. The CFTM gauge of 4 mm in diameter consists of 2 thermocouples of J type. One of the thermocouples is placed at the gauge surface whereas the other one is placed in the gauge body, at 6mm in depth. Wall heat flux was calculated from the temperature profiles measured by thermocouples [2].

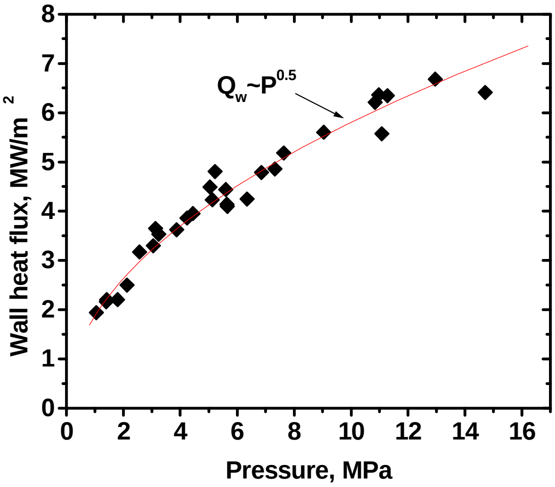

Fig.1. Pressure evolution of maximal wall heat flux density.

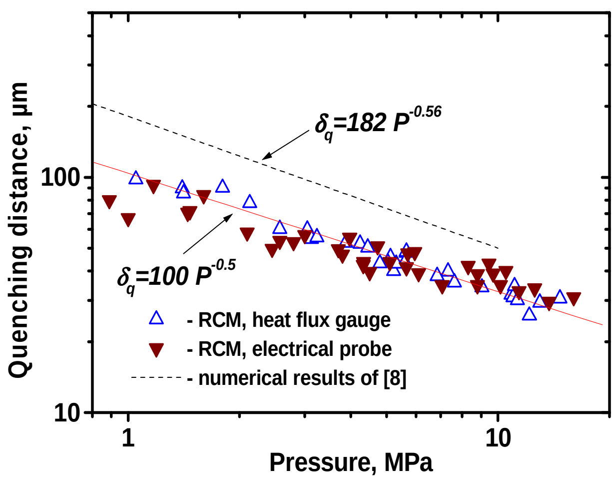

Fig.2. Quenching distance versus pressure.

Pressure evolution during combustion has been recorded with pressure transducer Kistler 601A, coupled to charge amplifier Kistler 5011B10.

Additionally to the heat flux and the pressure recording, an electrical probe technique [4,5] was used to study the flame quenching. The measuring electrode of the electrical probe is 2mm in diameter. It was flush mounted with the wall surface like the heat flux gauge. In experiments the electrical probe was placed symmetrically to the heat flux gauge, in opposite lateral chamber wall. An alternating negative voltage of a frequency of 10 kHz was applied to the electrical probe. A detailed description of the electrical probe design and its signal's post-treatment procedure is given in [4,5]. The flame quenching distances were obtained from these treatments.

Direct visualization of combustion process were carried out with a PHOTRON APX-RS 3000 camera providing resolution of 256x384 pixels, 1024 grey levels and allowing the recording of 20 000 images/s.

During the flame-wall interaction experiments the unburned gas temperature was 800-900K. Pressure during quenching is constant. Experiments were carried out in the pressure range of 0.8-16MPa. It is worth noting that in all experiments the wall surface remained at initial temperature (~293K) until the flame quenching.

3 Results and discussion

Results of the wall heat flux measurements are shown in Fig.1. Here the maximal wall heat flux density, Q_w, is given versus pressure at the instant of flame quenching. In all the pressure range, the maximal wall heat flux density increases monotonically with a pressure rise reaching the value of 6.5 MW/m^2 at the pressure of 15 MPa. As it is seen in Fig.1, for head-on flame quenching the pressure evolution of maximal wall heat flux density can be fitted by the polynomial $Q_w=1.84{\cdot}P^{\,0.5}$ where Q_w and P are in *MW/m*^{2} and *MPa*, respectively.

According to thermal formulation for single-wall quenching of transient laminar flame [3], the quenching distance δ_q can be estimated from wall heat flux as following:

$$\frac{\delta_q}{\delta_L}=\frac{1-\varphi}{\varphi}; \qquad \varphi=\frac{Q_W}{Q_\Sigma}\ , \quad \text{and} \quad \delta_L=\frac{\lambda}{\rho_u\cdot S_u\cdot c_P}, \qquad (1)$$

where δ_L, λ, c_P and S_u are the laminar flame thickness, the thermal conductivity, the specific heat at constant pressure and the flame burning velocity [7], respectively. The flame power Q_Σ is defined as $Q_\Sigma=\rho_u\cdot S_u\cdot Y_{fuel}\cdot\Delta H$, where ρ_u, Y_{fuel} and ΔH are the density of unburned mixture, the fuel mass fraction and the heat of combustion, respectively. This theoretical evaluation of quenching distance based on Eq.(1) was proved by direct visualization of flame position near the wall in the pressure range of 0.08-0.35MPa.

Dimensionless values φ of wall heat flux densities linearly decreases from 0.08 to 0.06 when pressure increases from 1 to 15MPa. In our experimental conditions, we could deduce that wall heat losses less than 10% of flame power are enough to quench the flame.

From a practical point of view it is interesting to compare obtained values of quenching distance with ones obtained with alternative diagnostics based on the use of electrical probe technique. According to [4] where a simple model of flame/probe interaction is proposed, the quenching distance can be linked to the probe current through the following relation:

$$\mathrm{j}=\frac{9}{8}\frac{\mu_i\varepsilon_0 U^2}{\delta_q^3}, \qquad (2)$$

where j, μ_i, ε_0 and U are the current density (A/m^{-2}), the ion mobility, the space permittivity and the bias voltage. It was previously demonstrated [4] that this model is validated in a pressure range of 0.05-0.5 MPa. The δ_q evaluation from electrical probe signal was proved by simultaneous measurements of electrical current and direct visualization of quenched flame in vicinity of the wall over low pressure range where optical technique allows such measurements.

Pressure evolution of quenching distance evaluated by using Eq.(1) and Eq.(2) are shown in Fig.2. Up and down triangles correspond to the evaluation of quenching distance from measured values of wall heat flux density and ionization current. Quenching distance values obtained from the electrical probe measurements (see Fig.2) correlate well with the δ_q evaluated from the wall heat flux measurements. Evaluation of quenching distance was made for a pressure range higher than in previous works. It is worth noting that these two independent methods of δ_q estimation give the same result for this pressure range. Thus we can suppose the validity of the two methods and values of quenching distance in the pressure range of 0.8-16MPa.

Pressure evolution of quenching distance can be fitted by the polynomial equation δ_q=a$\cdot P^b$, where a =100 and $b=-0.5$ for the pressure range of 0.8-15MPa. Here δ_q and P are in μm and *MPa*, respectively. Obtained experimental tendency of $\delta_q=f(P)$ is compared with one predicted in numerical study of Westbrook et al. [8] for the pressure range up to 4MPa. Numerical prediction is shown in Fig.2 by dash lines. In logarithmic scale the slop of numerical approximation is about the same as our approximation of experimental data. We suppose that the little difference between experimental and numerical values is due to higher temperature of unburned gas in our experiments.

4 Conclusion

Measurements of wall heat flux and ionization current were carried out with stoichiometric methane-air mixture in head-on quenching configuration for the pressure range of 0.8-16MPa. It was found that wall heat flux grows with pressure increase as $P^{0.5}$. However the dimensionless wall heat flux decreases with a pressure rise. Thus in our experimental conditions we could deduce that wall heat losses less than 10% of flame power are high enough to quench the flame.

It is experimentally founded that quenching distance values evaluated from wall heat flux and electrical probe current decrease with a pressure rise. These independent methods give the same result in the pressure range of 0.8-16MPa. Minimal value of quenching distance obtained at the pressure 15MPa is about 30µm. Pressure evolution of quenching distance would be fitted by the power polynomial $\delta_q \sim P^{-0.5}$.

Taking into account good correlations of quenching distance evaluated with heat flux and electrical probe techniques the value of maximal wall heat flux would be determined from ionization current measurements at known pressure.

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