Photoemission measurements of a gas temperature behind reflected shock waves

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Abstract

The photoemission method of temperature measurements with a 1 μs time resolution is presented. The technique was applied for recording current gas temperatures in reacting flows behind the shock waves reflected from plane and conical walls. It is shown that calculated and experimental temperatures are in good agreement.

Introduction

There are some difficulties in temperature measurements of hot gases with a high time resolution, especially, when fast chemical reactions occur between different gas components. Usually, if we want to use some optical technique for those measurements it is necessary to know the emissivity of an object. In the most cases, the emissivity is unknown. Besides, the emissivity itself depends on temperature. A method of temperature measurement with the 1 μs time resolution is presented in this report.

As follows from the Einstein law for the photoeffect, the photoelectron energy distribution depends on the quantum energy of electromagnetic radiation. The quantum energy rising of monochromatic radiation increases the maximum and most probable velocities in the Maxwell photoelectron distribution in the vicinity to the photocathode. Using different methods, one can detect and measure this changing of energy distribution, for example, in the photoelectric device it can be made by measuring photocurrent cutoff voltages for normalized monochromatic light fluxes or for heat fluxes at constant temperature [1]. Light fluxes are normalized to the photocurrent I_0=const, when a retarding voltage at control electrode is zero $U_r = 0$.

The quantity of electrons of different energies in an electron spectrum emitted under radiation of any wavelength does not depend on the light flux value. That is why, the ratio $m=I_0/I$ of non-modulated (upper) and modulated (low) currents of the photomultiplier within the linearity of its characteristic is the value characterizing the given wavelength λ or temperature T. When temperatures are identified through this value, one can deal with non-normalized light fluxes. It much simplifies measurements, as the measurement of an object spectrum is reduced to obtaining the ratio of m(λ) or m(T). The monochromatism of the light flux should be known a priori. The temperature is identified by the previous calibration – by the dependence of the retarding voltage U_r (or the photocurrent I at a constant retarding voltage) on a temperature T: $U_r = f(T)_{|Io=const}$ or $I = f(T)_{|Io=const,\ Ur\ =\ const}$, or by the relation m = f(T).

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Two properties of this method make it very useful. At first, there is no necessity to use some disperse or focusing optics. This causes the greatest possible optical efficiency of the photoemission device. This permits one to measure the radiation of low luminous objects. The second property is the simplicity of photoelectron modulation at frequencies of 1 MHz and more. This allows performing measurements in fast phenomena [1,2]. For instance, when the rate of temperature changing is 10^8 K/s.

The photoemission method can be applied for temperature measurements of hot gases or plasma, only if its line or band spectrum is similar to a continuous spectrum. Such conditions are satisfied at high pressures or at high density of spectrum lines in the spectrum interval, in which the temperature is measured. In other words, the luminous radiation should be thermal and locally equilibrium in nature. For example, this method can be applied for temperature measurements of particles in the heated gas flow. The radiation of an ensemble of heated particles in the shock tube theoretically approximates the radiation of an absolutely black body. So, we can apply this method for temperature measurement in the shock tube and also during the chemical processes, when there the local equilibrium conditions are reached.

Measurement technique

A sensor is a photomultiplier (PMT). Modulating rectangular pulses are applied to a control electrode of the PMT. In Fig. 1 the schematic of the photoemission pyrometer is presented. Radiation from object 1 through collimator 2 illuminates photocathode 3 of photomultiplier 4. The light flux can be decreased by neutral filter 5. A signal from the PMT anode through amplifier 6 comes to an input of digital oscillograph 7. For photoelectron modulation, generator 9 permanently supplies rectangular pulses of a duration of 1 μs to control electrode 8. The display of computer 10 shows a video pulse U(t). The temperature can be obtained via registering the modulated photocurrent and current ratios of m(t). By using available calibration curve m(T) the temperature T(t) one can be obtained.

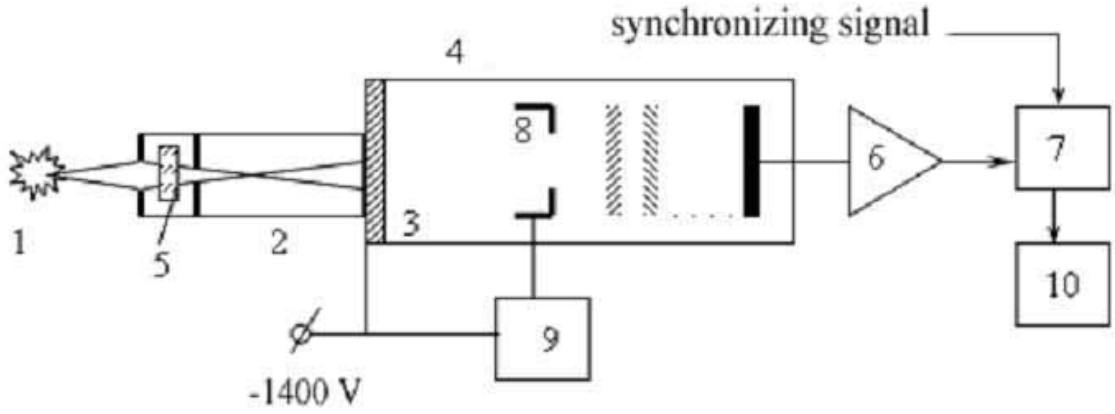


Figure 1. Schematic of the pyrometer

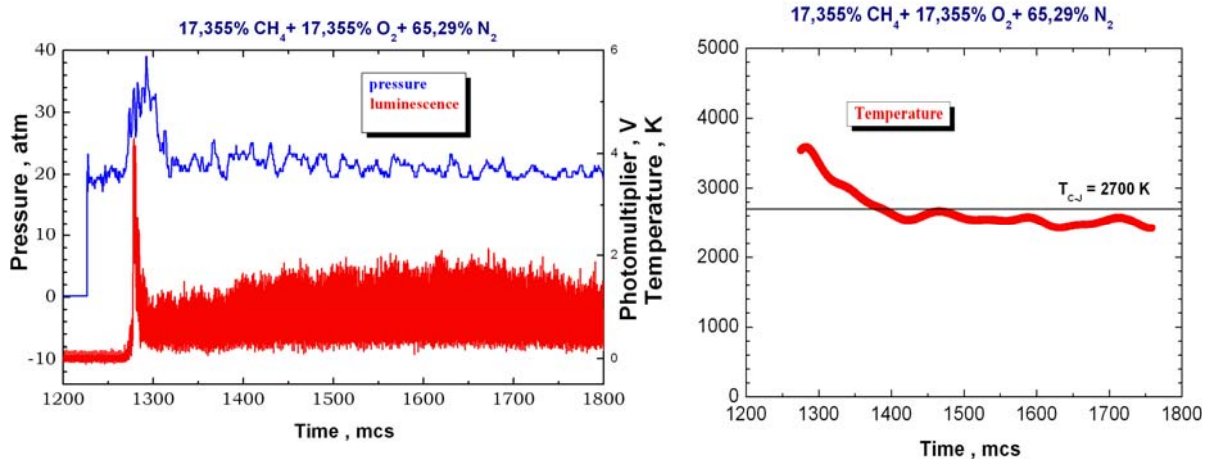
Experimental

The object of research was the luminescence of methane/hydrogen/air mixtures at auto-ignitions behind reflected shock waves. The stainless steel shock tube 76 mm in diameter and 8.5 m long with a reflected plane and conical walls was applied for these studies. High-frequency pressure sensors were used for pressure monitoring along the tube. To detect the luminescence the 8 mm quartz rods were mounted into the end wall, from which the radiation impinges on the registering PMT tube. Post-shock

conditions were determind from incident shock wave velocity measurements by the 1-D shock relations, assuming vibrational equilibrium and frozen chemistry [3,4].

Owing to the nonuniformity of a gas its temperature was not constant in time and in different cross-sections of the shock tube. The result is averaged over temperature along an observation path because the photoemission pyrometer detects the luminescence coming from different locations along the tube.

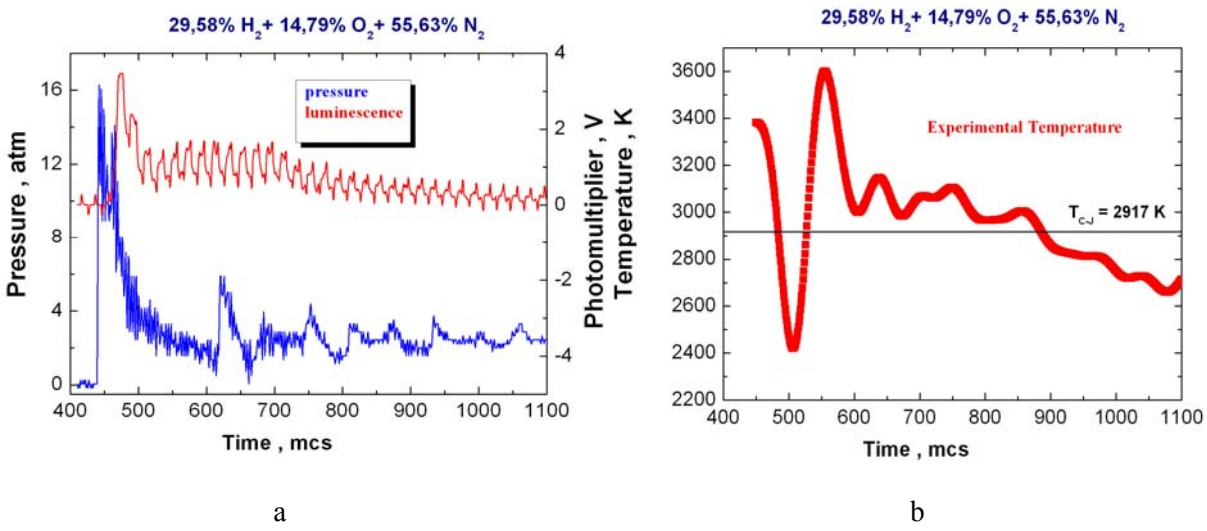
For auto-ignitions of methane/air mixtures all luminosity records were obtained at identical experimental post-shock conditions. During the first 6 μs we registered the low luminescence that was 5-6 times higher than a dark current. Then the flash of main luminescence follows, for which one luminosity peak increases more than 20 times and reaches a maximum value. The duration of this second phase is 6 – 8 μs. In the third phase the light flux decreases quickly 2 –3 times in the one- or two-stage process with the duration of each stage of about 30 – 50 μs. Then the light flux slowly decreases 5 – 7 times at 1 μs. The explosion of a rich methane/air mixture differs only by the last phase. The light flux increases during 600 μs after detonation. For a rich mixture (Fig. 2) the signal of pressure and luminescence (a) and calculated temperature (b) are presented. The calculated average temperature behind formed C-J detonation is about 2800 K. The predicted one T_{C-J} = 2700 K. So, the experimental results and predictions are in good agreement.



a b

Figure 2. Signal of pressure and luminescence (a) and calculated temperature (b) at auto-ignition of a rich methane/air mixture 17.355%CH_4+17.355%O_2+65.29%N_2 behind the reflected shock wave

The similar experiments in stoichiometric hydrogen/air mixtures were performed at shock wave reflection from a conical cavity. The studies were performed for strong auto-ignitions when the detonation was instantaneously formed in the localized focusing area in the vicinity of the cavity apex [5,6]. Fig. 3 shows the results of pressure and luminescence observations (a) and corresponding temperature calculation (b). The first temperature spike ≈ 3400 K exceeds the equilibrium C-J temperature because of the significant local primary gas compression. The next detonation expansion results in the visible gas cooling due to rarefaction of combustion products. The subsequent reflection and converging of bow shocks from the side wall of the tube results in the secondary axial gas compression and occurrence of the second temperature spike ≈ 3600 K. When steady state detonation is already propagated in the post-shock flow behind the incident shock wave at 600 – 900 μs, the predicted temperatures 2900 -3040 K corresponds well to the calculated equilibrium T_{C-J} = 2917 K.



a b

Figure 3. Signal of pressure and luminescence (a) and calculated temperature (b) at auto-ignition of a stoichiometric hydrogen/air mixture behind the shock wave reflected from a cone

Conclusion

The photoemission method for temperature measurement with a 1 μs time resolution was described. The technique was applied for recording current gas temperatures in reacting flows behind the shock waves reflected from plane and conical walls. It is shown that calculated and experimental temperatures are in good agreement.

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