HYPERSPECTROMETRY OF PROPANE–AIR FLAME

V. S. Ivanov[1], S. M. Frolov[1,2], I. V. Semenov[2], I. D. Rodionov[1], A. N. Vinogradov[3], and M. A. Gomorev[3]

[1]N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation
[2]Scientific Research Institute for System Analysis of the Russian Academy of Sciences, 36-1 Nakhimovskii Prosp., Moscow 117218, Russian Federation
[3]Joint-Stock Co. "STC Reagent," A-190, Post Box No. 192, Moscow 125190, Russian Federation

Abstract: Self-luminosity of a McKenna burner flame of a homogeneous propane–air mixture with a fuel-to-air equivalence ratio of $\Phi = 0.8$, 1.0, 1.6, 2.5, and ∞ in the near-infrared (950–1700 nm) and visible (400–700 nm) spectral ranges is investigated using spatially and temporally resolved scanning hyperspectral imaging. Spectral images of the flame are obtained at heights of 15 and 150 mm from the burner surface. Near-infrared radiation is primarily recorded at the wavelengths of 1300–1600 nm, although mixture enrichment with fuel results in elevated radiation intensity in the 1100–1200-nanometer range. Combustion of fuel-rich mixtures leads to the formation of soot and smoke particles generating background Planckian (blackbody) radiation with a maximum intensity near 1200 nm. Significant radiation intensity in the visible range is observed only at $\Phi > 1$, and the spectrum shape corresponds to Planckian radiation. The spatial resolution of the hyperspectral camera allows measurements of the radiation spectra in the central and peripheral regions of the flame. It turns out that at $\Phi > 1$, the spectra in these parts of the flame differ in both the near-infrared and visible ranges: in the near-infrared range, unreacted hydrocarbons are detected in the central part of the flame, while in the peripheral part, these hydrocarbons react with the surrounding air; in the visible range, the spectrum in the central part of the flame has a shape corresponding to Planckian radiation, while in the peripheral part, local maxima corresponding to water radiation are recorded. The presence of unreacted hydrocarbons and soot particles in the central part of the propane–air flame of the McKenna burner and their afterburning in the surrounding air in the peripheral part of the flame are confirmed by three-dimensional gasdynamic calculations using a detailed kinetic mechanism.

Keywords: hyperspectrometer; flame; self-luminosity; propane–air mixture; combustion efficiency; near-IR spectrum; visible spectrum

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Figure Captions

Figure 1 Photograph (*a*) and schematic (*b*) of the head of a McKenna burner. Dimensions are in millimeters

Figure 2 Photographs of the flames under study: (*a*) $\Phi = 0.8$; (*b*) 1.0; (*c*) 1.6; (*d*) 2.5; and (*e*) $\Phi = \infty$

Figure 3 Optical system of the near-infrared light hyperspectrometer

Figure 4 Layout of the hyperspectrometer (*a*) and photographs of the experimental setup (*b*). Dimensions are in millimeters

Figure 5 Example of hyperspectral recording of a fuel-rich propane–air flame at a height of $0.3D$ above the burner. Exposure time is 60 ms

Figure 6 Selection of central and peripheral zones for averaging spectral characteristics of the propane–air flame using three different hyperspectral flame images; left — stoichiometric flame at a height of $0.3D$; middle — fuel-rich diffusion flame at a height of $3D$ above the burner; and right — fuel-rich diffusion flame at a height of $0.3D$ above the burner. Colored frames highlight the averaging zones in the central (yellow frame) and peripheral (green frame) zones of the flame

Figure 7 Averaged spectra in the central (*1*) and peripheral (*2*) zones of fuel-lean (*a*), stoichiometric (*b*), fuel-rich (*c*), and fuel-rich diffusion (*d*) propane–air flames in the near-infrared range at a height of $0.3D$ above the burner

Figure 8 Averaged spectra in the central (solid curves) and peripheral (dotted curves) zones of fuel-lean (*a*), stoichiometric (*b*), fuel-rich (*c*), and fuel-rich diffusion (*d*) propane–air flames in the near-infrared range at a height of $3D$ above the burner. The red and blue colors of the lines correspond to different scales of signal magnitude representation along the Y-axis

Figure 9 Normalized spectra of a fuel-rich diffusion propane–air flame at a height of $3D$ above the burner at various highlighted points 1–4 of the hyperspectral image. The inset on the right shows the change in the flame image cross section over time

Figure 10 Spectra of a fuel-rich diffusion propane–air flame in the near-infrared range in comparison with the reduced spectrum of the black body calculated for different temperatures: *1* — spectrum averaged over the central zone of the flame at a height of $0.3D$ above the burner (*a*) and at a height of $3D$ above the burner (*b*); *2* — spectra of the flame at a height of $3D$ above the burner at point 3 without spatial averaging (*c*) and at point 4 without spatial averaging (*d*); the positions of the points correspond to Fig. 9; and *3* — reduced blackbody emission spectrum at a temperature $T = 1850$ (*a*) and (*b*), 1500 (*c*), and 2100 K (*d*)

Figure 11 The spectrum of a fuel-rich diffusion propane–air flame averaged over the central zone of the hyperspectral image obtained in the visible and near-infrared ranges at a height of $3D$ above the burner (*1*); and *2* corresponds to the reduced blackbody emission spectrum at a temperature of 1850 K

Figure 12 Instantaneous spectra of a fuel-rich diffusion propane–air flame in the near-infrared range at a height of $0.3D$ above the burner. Time sampling is 20 ms. The inset on the right shows a spatiotemporal scan of the hyperspectral image exhibiting brightness pulsations

Figure 13 The computational domain and basic computational mesh (*a*) and an example of the predicted velocity field in a fuel-rich diffusion propane–air flame (*b*). Dimensions are in millimeters

Figure 14 Predicted distributions of temperature (*a*) and mass fractions of CO_2 (*b*), H_2O (*c*), CO (*d*), OH (*e*), CH_2O (*f*), C_5H_{10} (*g*), and C (*h*) in four flames (from left to right): fuel-lean, stoichiometric, fuel-rich, and fuel-rich diffusion. The positions of the measurement cross sections $0.3D$ and $3D$ are shown by thin dashed lines in Figs. 14*a*, 14*c*, and 14*h*

Table Captions

Table 1 Flames under study (fuel-lean, stochiometric, fuel-rich, fuel-rich diffusion, and fuel-rich sooting)

Table 2 Characteristics of the visible light hyperspectrometer

Table 3 Characteristics of the near-IR light hyperspectrometer

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Contributors

Ivanov Vladislav S. (b. 1986) — Doctor of Science in physics and mathematics, acting director, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation; ivanov.vls@gmail.com

Frolov Sergey M. (b. 1959) — Doctor of Science in physics and mathematics, head of department, head of laboratory, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation; professor, National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 31 Kashirskoe Sh., Moscow 115409, Russian Federation; leading research scientist, Federal State Institution "Scientific Research Institute for System Analysis of the Russian Academy of Sciences," 36-1 Nakhimovskii Prosp., Moscow 117218, Russian Federation; smfrol@chph.ras.ru

Semenov Ilya V. (b. 1973) — Candidate of Science in physics and mathematics, head of department, Scientific Research Institute for System Analysis of the Russian Academy of Sciences, 36-1 Nakhimovskii Prosp., Moscow 117218, Russian Federation; ilyasemv@yandex.ru

Rodionov Igor D. (b. 1951) — Doctor of Science in physics and mathematics, head of laboratory, N. N. Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences, 4 Kosygin Str., Moscow 119991, Russian Federation; ir@reagent-rdc.ru

Vinogradov Alexey N. (b. 1978) — Candidate of Science in physics and mathematics, head of department, Joint-Stock Co. "STC Reagent," Moscow 125190, A-190, Post Box No. 192; al.n.vinogradov@gmail.com

Gomorev Mikhail A. (b. 1985) — specialist, Joint-Stock Co. "STC Reagent," A-190, Post Box No. 192, Moscow 125190, Russian Federation; gomorevma@gmail.com