

# Thermometry of an open spatially inhomogeneous flame by diode laser absorption spectroscopy

V.V. Liger, V.R. Mironenko, Yu.A. Kuritsyn, M.A. Bolshov

**Abstract.** Features of a single-beam variant of diode laser absorption spectroscopy (DLAS) used for temperature measurements in a spatially inhomogeneous hot zone are studied. A flame temperature of a commercial burner is measured by using water molecule absorption lines. The flame is probed by a diode laser radiation at various heights and in various directions. The correctness of DLAS measurement results is verified by comparing DLAS data with temperatures measured by the method of coherent anti-Stokes scattering (CARS). It is shown that in homogeneous flame domains the temperatures obtained by both the methods coincide. Temperature inhomogeneity along the probe beam direction is a principal problem of DLAS, in which case the method yields information about some effective temperature along the light trace. The difference in data obtained by DLAS and CARS is estimated. In probing traces with temperature gradients the difference reaches 700 K. Possibilities of accounting for temperature inhomogeneities along the trace in DLAS measurements are discussed. A method of differential spectra is suggested, which in certain conditions can provide substantially better coincidence of results for the two methods.

**Keywords:** absorption spectroscopy, diode laser, CARS, temperature measurement.

## 1. Introduction

Laser spectroscopy methods are widely used for diagnosing hot zones and burning processes in mixed sub- and supersonic gas flows [1, 2]. One of the mostly widespread and relatively simple methods for diagnosing such zones is diode laser absorption spectroscopy (DLAS) [3, 4]. This method has an advantage of remote temperature measurements in a hot zone, which is the necessary condition for obtaining authentic data, because introducing into a flow any kind of sensor such as thermocouple substantially distorts characteristics of the flow. In addition, this method provides temperature measurements with a high time resolution.

DLAS is based on the detection of absorption spectra of test molecules along the propagation path of probe radiation of a wavelength-tunable diode laser (DL). A gas temperature

in the test zone is determined by the ratio of integral intensities for, at least, two absorption lines in the transitions starting from substantially different levels. These intensities can be found in fitting by either individual line profiles or spectral parts comprising several absorption lines [5].

Presently, most works concerning diagnosing with the DLAS method are based on the assumption about homogeneous distributions of temperature and absorbing particle concentration along the measurement path inside the hot zone. However, obviously, these parameters are not spatially homogeneous in real power devices; with standard methods of detection and processing experimental absorption spectra, DLAS can only determine some average temperature and absorption particle concentration along the probe trace. The main problem, which hinders processing of experimental data in cases of such inhomogeneous distributions, is variation of the temperature and absorbing particle concentration, which affects both profiles and integral intensities of absorption lines along the probe trace. As a result, some integral profiles and intensities of spectral lines are experimentally recorded, from which average medium parameters are calculated after processing.

There are two main factors, which distort absorption spectral line profiles in a spatially inhomogeneous medium: (i) absorption of probe laser radiation outside the hot zone in a passage from a DL to the photodetector of recording system; and (ii) a temperature drop (gradient) from the maximal value to colder external layers inside the tested zone itself. To a certain degree, the first factor can be suppressed by blowing an inert gas through a volume outside the tested object, where the DL beam passes or by using absorption transitions with highly lying low-energy levels (with the energies of above  $1500\text{ cm}^{-1}$ ). In addition, as a test molecule one can use molecules, which are not comprised in the laboratory room air. However, the second factor remains in probing any real hot zone.

A radical approach to overcome the problems arising in determining the parameters of inhomogeneous media by DLAS is tomographic measurements [6]. To this end, the radiation beams of probe lasers are split by optical splitters to several beams, which then cross the test zone in various directions. This approach yields information about distributions of medium parameters; however, the optical scheme of a DLAS spectrometer and the procedure for processing experimental spectra are substantially complicated. Tomographic measurements are realised in the case of hot streams freely flowing to the atmosphere but are impossible in various cross sections of closed power devices, where input of the optical radiation is limited by their design.

There is also the possibility of determining the temperature of a hot zone by the method of coherent anti-Stokes light

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scattering (CARS) [7, 8]. Since CARS provides temperature measurements in a narrow local domain where the probe laser beams intersect, it is capable of measuring a local temperature at an arbitrary point of the hot object. The temperature distribution itself can be found by the CARS method with a sufficient accuracy and this approach can serve as the reference method for estimating deviations of the 'effective' temperature found by the single-beam DLAS method from the maximal temperature in the hot zone.

In the present work, we experimentally study the influence of the spatial inhomogeneity of hot object parameters on the accuracy of temperature estimates by the single-beam DLAS method. We are also aimed at developing methods for increasing the accuracy of such estimates by changing the measurement scheme and algorithms for processing experimental absorption spectra.

As a model for test temperature measurements in a spatially inhomogeneous object we choose a burner laminar flame, in which the burning mixture content and the fuel and oxydant flow rates can be smoothly varied and reproduced. In stationary atmospheric conditions in the workroom, the temperature distribution in a flame of such a burner can be considered sufficiently reproducible, whereas a substantial variation of temperature and the mixture density in the direction from the flame centre to periphery is a good model of spatially inhomogeneous distribution of these parameters.

The temperatures in various flame domains obtained with DLAS were compared to published results of flame characterisation for the same domains and a similar burner by the CARS method of local thermometry [9].

## 2. Physical foundations of the method

DLAS is based on measuring the ratio of integral intensities of the absorption lines of the tested molecule, corresponding to transitions from different low energy levels. In the conditions of thermodynamic equilibrium (which are actually always satisfied at an atmospheric pressure and detection times of longer than 1 $\mu$ s) and a homogeneous distribution of temperature and test molecule concentration in a probed domain, the ratio of the line integral intensities only depends on the medium temperature.

Light propagation through an absorbing medium is described by the Bouguer–Lambert–Beer law, which, in the case of a homogeneous medium, weak absorption, and single line, is given by the expression

$$I_v = I_{v0} \exp[-S(T)g(v - v_0)NL] \\ \approx I_{v0} - I_{v0}S(T)g(v - v_0)NL. \quad (1)$$

Here,  $I_v$  is the intensity of a monochromatic radiation with a frequency  $\nu$  after passing a path of length  $L$ ;  $S(T)$  is the transition line strength of the absorption line for a certain transition with the centre frequency  $\nu_0$ ;  $g(\nu - \nu_0)$  is the profile of this line; and  $N$  is the concentration of absorbing particles. The line strength depends on temperature  $T$  and its profile depends on the temperature, pressure, gas composition, and the mechanism of broadening. At pressures not much distinct from atmospheric pressure, the spectral line profile  $g(\nu - \nu_0)$  is conventionally described by the Voigt function. A typical HWHM of an absorption line in the diagnosis of gas flows and flames is  $\sim 0.1 \text{ cm}^{-1}$  (3 GHz); hence, radiation of a single-mode (sin-

gle-frequency) DL with a line width of 10–50 MHz can be considered as monochromatic and Eqn (1) can be used for interpreting results of absorption measurements at a high accuracy.

For the ratio  $R$  of the two line strengths chosen for measurements  $S_1/S_2$  we have the expression

$$R = \frac{S_1}{S_2} = \left( \frac{S_1}{S_2} \right)_{T_0} \exp \left[ -\frac{hc\Delta E''}{k} \left( \frac{1}{T} - \frac{1}{T_0} \right) \right], \quad (2)$$

where  $(S_1/S_2)_{T_0}$  is the ratio of the line strengths at certain temperature  $T_0$ ; and  $E''$  is the energy gap between the lower states of the corresponding transitions. One can see that this ratio is a single-valued function of temperature.

The line strengths for many transitions of the most of simple molecules at room temperature are known and can be found in databases (HITRAN [10], HITEMP [11]).

In experiments, a transmission spectrum is recorded  $I_\nu$ . If the temperature and molecule concentration are homogeneously distributed and absorption is weak, the value of  $S(T)$  is related to the absorption coefficient  $\alpha(\nu)$  as follows:

$$\alpha(\nu) = (I_{\nu_0} - I_\nu) / I_{\nu_0} = S(T)g(\nu - \nu_0)NL. \quad (3)$$

If the line widths similarly depend on temperature then  $R$  can be found from the intensity ratio at line centres. In the opposite case, it is necessary to calculate the integral absorption coefficient

$$A = \int \frac{I_{\nu_0} - I_\nu}{I_{\nu_0}} d\nu = S(T)NL. \quad (4)$$

If absorption at several lines is experimentally recorded then an efficient method of temperature measurement is fitting of a theoretical spectrum simulated from the spectroscopic databases to the recorded experimental spectrum [5]. Thus, from the results of simultaneous absorption measurements at several lines of a tested molecule one can calculate a temperature in the probe domain. From the absolute value of the integral absorption coefficient  $A = S(T)NL$  one can find a concentration of the absorbing component.

In the case of an inhomogeneous medium, expression (3) for the absorption spectrum should be modified to the form

$$\alpha(\nu) = \int_0^L S(T)g(\nu, T, P, N)N(l) dl, \quad (5)$$

where temperature  $T$ , pressure  $P$ , and molecule concentration  $N$  at each point of the tested volume depend on the point coordinate  $l$  along the laser beam axis. Within the limits of a laser beam cross section, the temperature and concentration of absorbing particles are assumed constant. The fitting of such a spectrum is much complicated under the conditions of large gradients of temperature and concentration along the measurement trace and in the general case is only possible if the corresponding distributions are known.

In the most of works, the temperature is determined under the assumption of its homogeneous distribution in the object tested. In this case, theoretical spectra are simulated from spectroscopic databases with just the temperature taken into account. If the temperature distribution is not homogeneous, various algorithms are used. In the present work, an experimental absorption spectrum formed along the entire trace of

the probe laser beam was fitted by the spectra simulated by using only the temperature. The temperature obtained in this way we will call an ‘effective’ temperature  $T_{\text{eff}}$ .

### 3. Experiment

#### 3.1. Burner

As an object for temperature measurements in a spatially inhomogeneous medium, we have chosen a laminar diffuse flame of a Wolfhard–Parker slot burner [12, 13] with the partial preliminary mixing of burning composition components. The burner is small, provides a stable flame and high reproducibility of the temperature distribution after repeated switching on. The flame has a plane shape and comprises both domains with homogeneous temperature distribution and zones of high temperature gradients. These characteristics allow one to use the burner as an etalon in taking measurements by various methods.

In all experiments, an enriched methane–air mixture was used. Precision electron fluxmeters used were capable of setting the fuel and oxidant consumption with an accuracy of  $0.01 \text{ norm L min}^{-1}$ , and the air consumption with accuracy of  $0.1 \text{ norm L min}^{-1}$  with attained high reproducibility of flame characteristics from start to start.

The burner case, in which fuel was partially premixed with an oxidant, is schematically shown in Fig. 1a. Flows of homogenised gas go separately through three slit channels with rectangular cross sections. Mixed fuel (methane) and oxidant (air) pass through a central channel of width 9 mm. Additional air passes through two side channels and forms a concurrent flow around the flame stabilising it. In this way, a quasi-stationary flow of heated gas is formed. The burner construction assumes the flame symmetry relative to the plane  $yz$ , almost homogeneous temperature distribution inside the flame along the burner slit (along  $y$  axis), and high temperature gradients in a passage through the flame front from the initial mixture towards combustion products. The burner is arranged on a moving base, which allows one to position the burner case with an accuracy of 0.01 mm (in the  $x$  axis), 0.25 mm (in the  $z$  axis), and 1 mm (in the  $y$  axis).

Photographs of a burning flame with an enriched methane–air mixture at the fuel excess coefficient  $\Phi = 2$  are shown

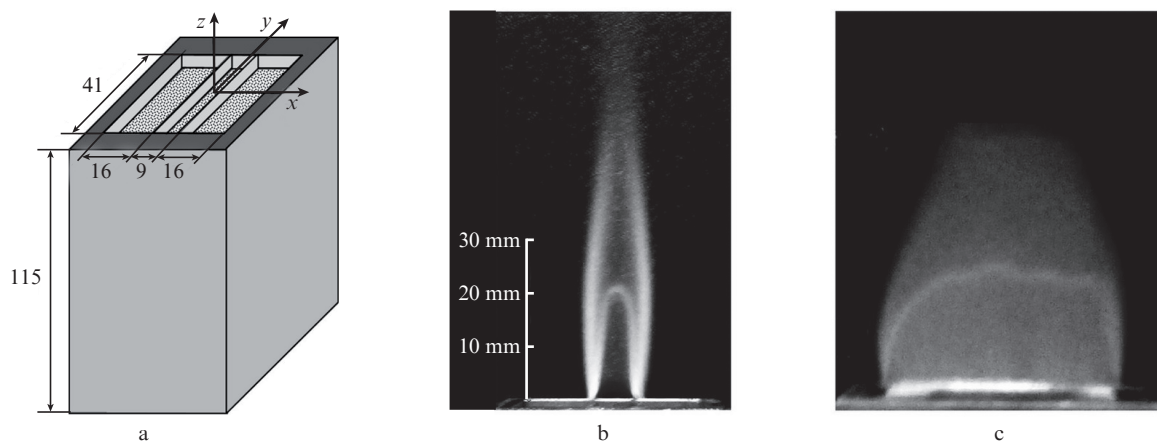
in Fig. 1b (across the flame plane) and Fig. 1c (along the flame plane). The flame symmetry relative to the plane  $yz$  is clearly seen, as well as the internal and external boundaries of a flame front. In particular, the height of the internal flame boundary is  $\sim 20 \text{ mm}$ .

This source was used in the comparison experiments performed by collaborators of the Institute of Spectroscopy RAS and General Physics Institute RAS in 2015 at the CIAM laboratory. In these experiments, results of the single-beam DLAS method were compared to those of local temperature measurements by the CARS method in similar regimes of burner operation. The data obtained are presented in [14] along with a description of a Wolfhard–Parker burner.

#### 3.2. Design of a DLAS spectrometer

In the present work, we used a DLAS spectrometer with two tunable-wavelength DLs developed for remote measurements of a temperature and water vapour concentration in gas flows at a mixture pressure of up to 3 atm in a temperature range of 300–2000 K. A detailed description of the spectrometer scheme, constituting units, procedures for data recording and processing are given in [15].

The diode lasers operate in a pulse-periodic regime, the supply current pulses are applied to the lasers one after another (time multiplexing). Radiation of the two DLs from the main unit is collected in an optical multiplexer to a single beam and passes to a single-mode fibre. The radiation formed by a gradient collimator at the fibre output (a beam diameter is  $\sim 1 \text{ mm}$ ) passes to an object being tested. Having passed through the test zone, the radiation is collected by an optical system to a photodetector, a signal from which is amplified in a preamplifier and passes through a stranded cable to a data detection and processing system. The system provides detection of the output powers of both the DLs in order to normalise processed absorption signals. Such normalisation is needed for taking into account variations of the DL radiation intensity under the tuning a wavelength of the latter by changing the injection current. To reduce noise and influence of various photodetectors, the probe beam passed through the flame and comprised of the beams of both DLs is detected by a single photodetector (InGaAs)



**Figure 1.** (a) Schematic of the burner (dimensions in mm) and (b, c) flame photos in (b) the transverse (along the  $x$  axis) and (c) longitudinal (along the  $y$  axis) directions.

with a sensitive surface diameter of 2 mm. The radiation frequency of each DL varies within its particular spectral range ( $\sim 3 \text{ cm}^{-1}$ ) for 20 ms, then the DL stops emission for the time lapse of 20 ms during which just the second DL operates. The frequency scale is calibrated by using a Fabry–Perot etalon. Thus, the minimal time needed for detecting experimental absorption spectra in the DLAS scheme described is  $\sim 40 \text{ ms}$ . In such a scheme, the photodetector permanently detects signals of the radiation passed through the tested zone, and the processing system separates signals from different DLs in turn.

Conversion of an analogue signal to a digital form takes  $\sim 65 \text{ }\mu\text{s}$  per sample. During the detection cycle of one laser (20 ms), 300 samples are digitised, from which 270 samples refer to the current pulse duration. The rest 30 samples (6 at the beginning and 24 at the end of the detection time interval) are used for determining a zero signal level when the laser is switched off. A total time of the recording process was  $\sim 10 \text{ s}$ , and so about  $\sim 260$  scans were recorded for each laser in this time lapse.

In the near-IR range, the absorption spectrum of the  $\text{H}_2\text{O}$  molecule consists of many lines, which overlap at pressures of above 1 atm. Two DLs operating in the ranges  $7185 \text{ cm}^{-1}$  ( $\lambda = 1.39 \text{ }\mu\text{m}$ ) and  $7444 \text{ cm}^{-1}$  ( $\lambda = 1.34 \text{ }\mu\text{m}$ ) were used in the spectrometer. The choice of the spectral ranges is related with the requirements to gas mixture parameter measurements at the mixture pressure of up to 3 atm and temperatures in the interval 500–2000 K [15].

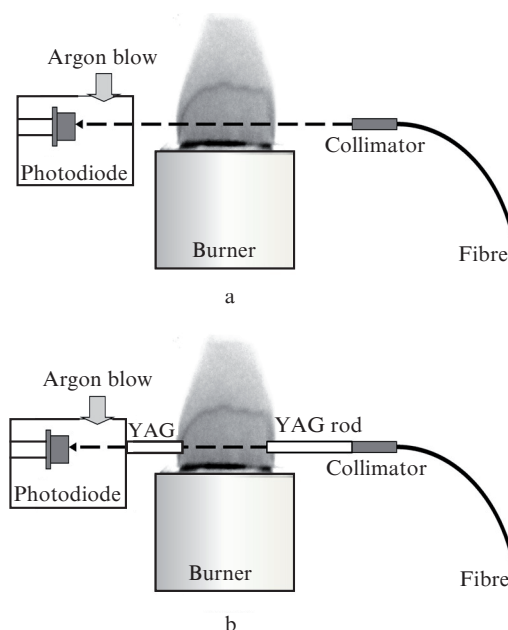
The DLAS spectrometer was tested for temperature measurements in stationary and spatially homogeneous conditions using a heated cell filled with water vapours; the results obtained in the range 500–1200 K were compared to those performed with a thermocouple and have confirmed the high accuracy, operation reliability, and simplicity [15]. The DLAS sensor developed in the present work was tested for diagnosing a spatially inhomogeneous source by using a commercial burner at atmospheric pressure.

## 4. Experimental results and discussion

In this section, we present results of determining the temperature of the spatially inhomogeneous hot zone of commercial burner flame. The ways of measurement result correction are discussed, which make it possible to find a temperature of the hottest zone in the flame while using a single-beam DLAS method.

### 4.1. Measurement of effective averaged temperature

The effective flame temperature was measured by using a DLAS spectrometer with the probe beam propagating both along (the  $y$  axis), and perpendicular (the  $x$  axis) to the flame plane at various heights  $z$  from the burner slit cut ( $z = 0$ ). A scheme of measurements in probing the flame along the  $y$  axis is given in Fig. 2. A collimator and photodetector were preliminarily adjusted and fixed so that the laser beam that passed through the flame was focused by the input optical system to a central part of the photodetector light sensitive area. The focusing to the centre of the light sensitive area substantially reduces signal fluctuations, which are determined by laser beam ‘jitter’ while passing the hot zone. It was experimentally established that if the beam is focused to periphery of the light-sensitive zone then signal intensity fluctuations

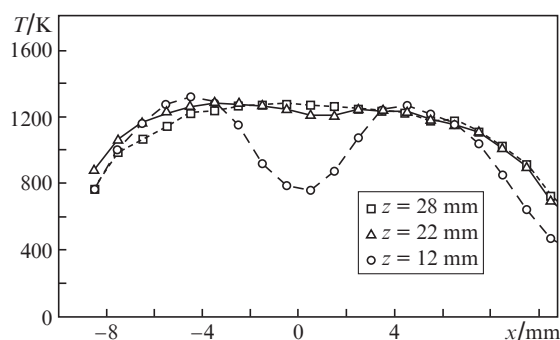


**Figure 2.** Optical scheme of experiments (a) without YAG rods and (b) with the rods.

sharply increase due to random shifts of the beam outside the sensitive area location.

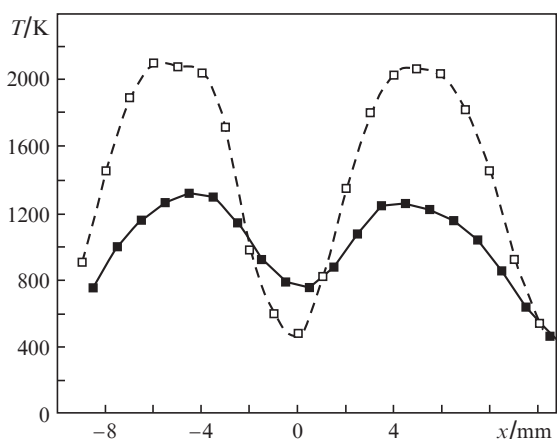
At fixed heights  $z = 12, 22,$  and  $28 \text{ mm}$  and measurements along  $y$  axis, the burner moved relative to the DL probe beam in a horizontal direction along  $x$  axis (from  $-12$  to  $+12 \text{ mm}$  with a step of  $1 \text{ mm}$ ). Between the flame and fibre end as well as between flame and an input optical unit there are airspaces of thickness  $\sim 35 \text{ mm}$ .

Measurement results for a transversal temperature distribution at various heights from a burner base (the point  $x = 0$  corresponds to the position of a flame symmetry plane  $yz$ ), are presented in Fig. 3 along with the profiles of effective temperatures at various heights calculated by the ‘single-temperature’ algorithm. One can see a two-humped temperature profile at the height of  $12 \text{ mm}$ , and profile ‘flattening’ at the heights of  $22$  and  $28 \text{ mm}$ . These distributions correctly reproduce a spatial profile of the flame temperature; however, the absolute values of the ‘integral’ temperatures determined in

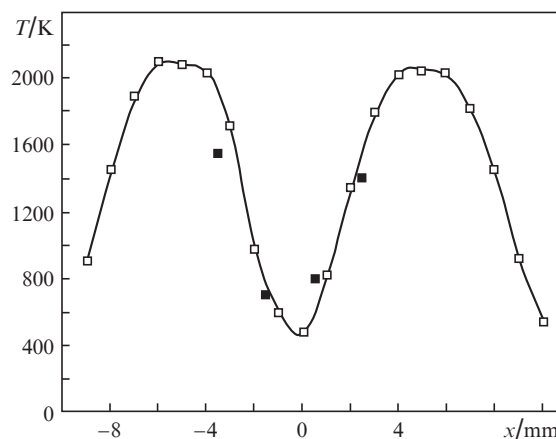


**Figure 3.** Distributions of ‘effective’ temperature in the flame transverse direction obtained by the DLAS method at various heights  $z$  from a burner base (points), curves are results of the calculation by the ‘single-temperature’ algorithm.





**Figure 4.** Transverse temperature distributions obtained by (■) DLAS and (□) CARS [9] methods at the height  $z = 12$  mm.



**Figure 5.** (□) Transverse temperature distribution at  $z = 12$  mm obtained by the CARS method with  $N_2$  molecules [9] and (■) results of temperature measurements by DLAS with YAG rods.

this way are substantially less than the local temperatures at the same flame parts determined by the CARS method.

In Fig. 4, DLAS data for height  $z = 12$  mm are compared to results obtained in a flame cross section by the plane  $xz$  (that is, at  $y = 0$ ) with the CARS spectra of  $N_2$  molecules [9].

From Figs 3 and 4 one can see that the results obtained with DLAS illustrate a characteristic two-hump profile of the temperature distribution along  $x$  axis in a bottom part of the flame; however, quantitative data substantially differ especially in high-temperature parts. It is natural to assume that the differences are related to the fact that DLAS is a ‘trace’ method, that is, DL radiation crosses not only the flame domain, but also a transfer zone where the temperature drops from the maximal value to approximately room temperature. This domain of a substantial temperature gradient makes a substantial contribution into the sum absorption spectrum and, thus, changes the values of the effective temperature obtained from the ratio of line integral intensities [see (2)].

We have verified this assumption by performing a series of experiments with two yttrium–aluminium garnet (YAG) rods of diameter 8 mm placed from two opposite sides into the flame. The rods are arranged between the fibre edge, from which the DL probe radiation passes, and the flame, and also between flame and input optics of the detection system (see Fig. 2b). The separation between the edges of rods inside the flame is 34 mm. The employment of rods made it possible to exclude the domains with high temperature gradients and detect an absorption spectrum in a sufficiently homogeneous flame zone. A pure argon blows the space inside the unit forming the DL probe radiation and the unit with input optics. In such a configuration, flame domains at a height  $z = 12$  mm with an approximately homogeneous temperature distribution along the measurement trace (along  $y$  axis) were tested by the DLAS method. The results are shown in Fig. 5.

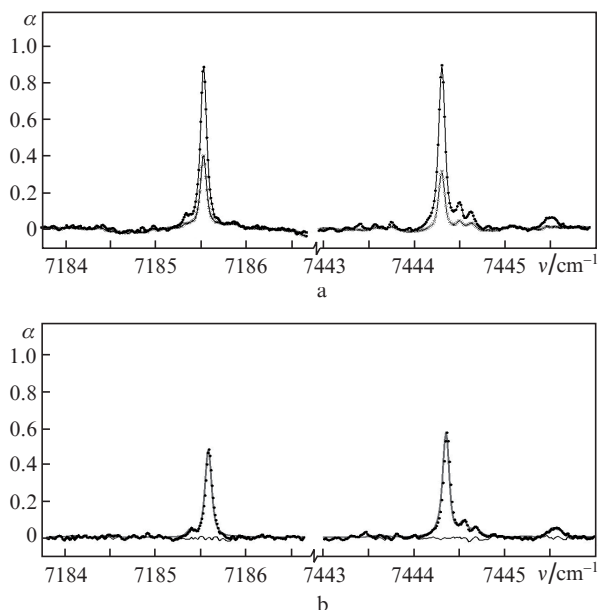
From Fig. 5, one can see that in this experimental series, the temperatures obtained with the DLAS method and with local CARS measurements are close. Unfortunately, a limited thermal resistance of YAG rods prevented measurements in the hottest points. This circumstance explains a fewer (as compared to Figs 3 and 4) number of experimental points detected by the DLAS method with YAG rods.

## 4.2. Method of differential spectra

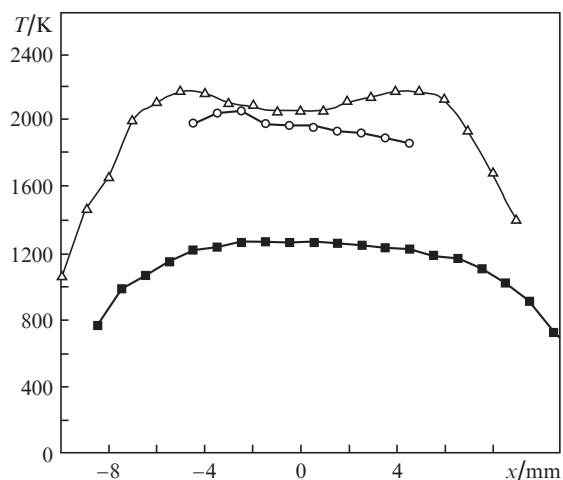
The effective temperature along a spatially homogeneous flame determined with the developed single-beam DLAS spectrometer in the chosen wavelength range and ‘single-temperature’ algorithms for processing experimental spectra is noticeably lower than the maximal temperature. A difference of this average temperature from the local temperature found by the CARS method [9] at the flame hottest points was 700–800 K, which is mainly determined by a contribution of edge zones with high temperature gradients.

For finding a temperature at the flame hottest zone above its front, we suggest the method of differential spectra. Applicability of the method is based on the fact that, according to literature data at heights  $z \geq 25$  mm the temperature of the hot zone is approximately constant both in the longitudinal ( $y$ ) and in transverse ( $x$ ) directions. In the first approximation the profiles of temperature variation from the maximal value in the hot zone to room temperature outside the flame are similar. The resulting spectra in both directions are superpositions of the absorption spectra in the hot zone and in the intermediate zones with a sharp temperature drop. The substantial difference in measurement results for two perpendicular directions is that the flame ‘thickness’ is substantially less than the ‘length’. Absorption spectra recorded in tests for two perpendicular directions at a height  $z = 28$  mm are presented in Fig. 6a. Assuming similar flame temperature gradients in the directions  $x$  and  $y$ , one can find the spectrum formed in a homogeneous part of the hot zone by subtracting the spectrum recorded in the transverse direction from that recorded in the direction along the flame. Results of such a procedure (differential spectra) are given in Fig. 6b. Both experimental spectra (points) and results of fitting (solid lines) the differential spectra by a single-temperature theoretical spectrum at  $T \sim 2000$  K are shown. Thus, processing by the method of differential spectra substantially enhances results of direct DLAS measurements (cf. Figs 3 and 4), which is illustrated in Fig. 7. The values obtained in the result of this correction coincide with data [9] within the corresponding errors.

Consider the error problem in more details. Statistical measurement errors can be estimated by calculating a temperature from a single spectrum detected in a single scan, in several scans, and in all 261 scans. This yields  $\Delta T = 240$  K



**Figure 6.** (a)  $\text{H}_2\text{O}$  absorption spectra in longitudinal and transverse directions with respect to the flame plane at a height  $z = 28$  mm and (b) differential spectra: (points) experiment and (solid curve) the result of fitting. The wavy thin line in (b) is a residual, that is, a difference between the experimental spectrum and the closest simulated one. See text for explanation.



**Figure 7.** Transverse temperature distributions at a height  $z = 28$  mm: (■) effective temperature obtained by DLAS, (Δ) local temperatures measured by CARS with  $\text{N}_2$  molecules [9], and (○) temperatures found from differential DLAS spectra.

(single scan), 140 K (4 scans), and 70 K (16 scans). By averaging over all 261 scans we obtain  $\Delta T = 20$  K.

A systematic error in temperature determination is related to the accuracy of line integral intensity calculations and spectroscopic databases accuracy. By estimating the error of determining parameter  $R$  [see (2)] as several percent, one can estimate the error of temperature calculation at a level of 100–150 K. These values are comparable with errors of determining temperature by CARS.

Emphasise a limitation of the method suggested. It can only be applied in cases of diagnosing a hot source with sub-

stantially different dimensions in perpendicular directions. If the object under investigation is a closed system then the method suggested can only be applied by complicating the test chamber construction and introducing additional channels for optical probing.

Note that a new algorithm for processing experimental spectra formed along the entire path of the probe beam, which allows one to estimate the maximal temperature in an inhomogeneous hot zone was suggested in our paper [16]. The algorithm implies fitting an experimental spectrum by not only a theoretical spectrum with a certain temperature, but a linear combination of ‘single-temperature’ spectra with the weights, which take into account contributions from hot and cold parts of tested object. A numerical simulation and experiments with two cells on the beam trace with controlled and adjustable parameters demonstrated the efficiency of the algorithm suggested.

## 5. Conclusions

By using the DLAS spectrometer developed, water absorption spectra are measured in the ranges of 7185  $\text{cm}^{-1}$  ( $\lambda = 1.39$   $\mu\text{m}$ ) and 7444  $\text{cm}^{-1}$  ( $\lambda = 1.34$   $\mu\text{m}$ ) in a stationary spatially inhomogeneous flame of a commercial burner. Correctness of the temperature measurements by the DLAS method was verified by comparing the temperature values obtained for various flame zones with results of local measurements by CARS with  $\text{N}_2$  molecules. In tests of flame zones with homogeneous temperature distributions, data obtained with DLAS method well agrees with results of CARS.

Zones with large temperature gradients along the probe trace result in a substantial discrepancy between the ‘effective’ temperature found by the DLAS method and the temperature determined by CARS. This discrepancy reaches 700 K at the maximal temperature of  $\sim 2100$  K.

A method of differential spectra is suggested, which implies flame probe in two perpendicular directions. Since the spatial distributions along and across the flame are rather similar, the differential spectrum obtained by subtracting the transverse spectrum from longitudinal one presents a spectrum corresponding to absorption in a homogeneous flame zone. Fitting of such differential spectra by spectra simulated with a single temperature yields a good agreement between DLAS and CARS methods.

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