



CROSSED-BEAM CORRELATION TECHNIQUE  
FOR TURBULENT-FLAMES MEASUREMENTS

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ABSTRACT

Emission-absorption spectroscopy methods for flame diagnostics have mostly been limited to axisymmetrical laminar flames. The development of tunable lasers with extremely narrow bandwidth has made possible the determination of time-averaged mean values of temperature and species concentration in axisymmetrical turbulent flames.

In this work, a new method is presented to allow the measurement of both time-averaged mean values and fluctuation intensities of temperature and species concentration in turbulent flames. With this method, turbulent flames -irrespective of their geometries- may be investigated. The possibilities of these measurements using the crossed-beam correlation technique are studied and presented.

The correlation between the fluctuation values of received radiation density of two laser beams crossed at a certain point in the turbulent flame gives information about the mean and fluctuation components of the spectral absorption coefficient at that point. Measurement of the absorption coefficient leads to determination of temperature and species concentration.

The fluctuation intensities are measured using crossed laser beams having the same wavelength, whereas time-averaged mean values are determined when the wavelengths of the laser beams are different.

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## 1. INTRODUCTION

For measuring temperature and concentration profiles in flames, the spectroscopic methods are preferable because they have no effect on the combustion process. Moreover, the development of lasers, with extremely narrow bandwidth, has given the spectroscopist new possibilities for measuring techniques.

The major disadvantage of the standard optical techniques, such as schlieren, interferometry, or emission-absorption spectroscopy, is that the measured quantity depends on an integral of the medium properties along the entire light path. Lueck and Mueller [1] have presented a method which allows the simultaneous measurement of temperature and species concentration in axisymmetrical laminar flames using absorption spectroscopy with a single laser beam.

Combustion processes in most practical applications are of turbulent nature. The time-averaged mean values of temperature and species concentration in axisymmetrical turbulent flames are measurable by means of one-beam laser absorption spectroscopy [2]. The variation of radiation intensity of the laser beam after passing through the flame is a function of temperature and species concentration averaged along the beam path. Abel integral transformation is followed to obtain spatial resolution of the measured averaged flame parameters.

In this work, the application of crossed-beam correlation technique for measuring local time-averaged mean values and fluctuation intensities of turbulent flame parameters is investigated. The main advantage of this method is that the measured parameters can be determined without the necessity of making assumptions concerning symmetry of the structure of the medium to be studied.

## 2. LASER TRANSPORT THROUGH TURBULENT FLAMES

The equation of transport of a laser beam through an inhomogeneous turbulent flame, neglecting the effect of scattering, may be written in the following form [1],[2]:

$$L_{\lambda}(b,t) = L_{\lambda}(0,t) \exp \left[ - \int_0^b k_{\lambda}(x,t) dx \right] \quad (1)$$

The instantaneous value for each of the spectral radiation density  $L_{\lambda}$  and the spectral absorption coefficient  $k_{\lambda}$  may be written as the sum of a time-averaged mean value and a fluctuation value as follows:

$$\begin{aligned} \overline{L_{\lambda}(b,t)} + L'_{\lambda}(b,t) &= \left[ \overline{L_{\lambda}(0,t)} + L'_{\lambda}(0,t) \right] \exp \left[ - \int_0^b \overline{k_{\lambda}(x,t)} dx \right] \\ &\quad \cdot \exp \left[ - \int_0^b k'_{\lambda}(x,t) dx \right] \end{aligned} \quad (2)$$

For the case where the characteristic turbulence length is relatively small with respect to the integration length  $b$ , the integral  $\int_0^b k'_\lambda(x,t) dx$  is sufficiently small to permit linearization of that part of the exponential, and Eq.(2) may be written as:

$$\overline{L_\lambda(b,t)} + L'_\lambda(b,t) = [\overline{L_\lambda(0,t)} + L'_\lambda(0,t)] \exp \left[ -\int_0^b \overline{k_\lambda(x,t)} dx \right] \cdot \left[ 1 - \int_0^b k'_\lambda(x,t) dx \right] \quad (3)$$

It should be noted that this linearization does not restrict this method to small fluctuations, because the integration of  $k'_\lambda$  from 0 to  $b$  represents a sum of a large number of statistically independent events. The value of this sum is always smaller than the sum of individual values of these events [3],[4].

The time averaged value of the spectral radiation density at the detector can, then, be written as:

$$\overline{L_\lambda(b,t)} = \frac{\overline{L_\lambda(0,t)} \exp \left[ -\int_0^b \overline{k_\lambda(x,t)} dx \right]}{1 - \int_0^b \overline{k_\lambda(x,t)} dx} \cdot \overline{L'_\lambda(0,t)} \int_0^b k'_\lambda(x,t) dx} \quad (4)$$

The fluctuation of the laser source  $L'_\lambda(0,t)$  is not correlated with the fluctuation of the local absorption coefficient in a turbulent flame, hence:

$$\overline{L_\lambda(b,t)} = \overline{L_\lambda(0,t)} \exp \left[ -\int_0^b \overline{k_\lambda(x,t)} dx \right] \quad (5)$$

and the received fluctuation value is:

$$L'_\lambda(b,t) = -\overline{L_\lambda(b,t)} \left[ \int_0^b k'_\lambda(x,t) dx - \frac{L'_\lambda(0,t)}{\overline{L_\lambda(0,t)}} \left\{ 1 - \int_0^b \overline{k_\lambda(x,t)} dx \right\} \right] \quad (6)$$

If the fluctuation of the light source is very small relative to its mean value, the second term in the big brackets may be neglected, and the following equation will be applicable:

$$L'_\lambda(b,t) = -\overline{L_\lambda(0,t)} \int_0^b k'_\lambda(x,t) dx \quad (7)$$

### 3. CORRELATION OF CROSSED BEAMS OF EQUAL WAVELENGTH

Referring to the beams arrangement, Fig.1, the fluctuation values for both beams  $Q_1D_1$  and  $Q_2D_2$ , intersecting at point  $(x,y,z)$ , measured at detectors  $D_1$  and  $D_2$  are determined according to Eq. (7):

$$\begin{aligned} L'_{1\lambda}(\lambda,t) &= -\overline{L_{1\lambda}(\lambda,t)} \int_{\alpha_{D_1}}^{\alpha_{D_1}} k'_\lambda(x+\alpha, y, z, \lambda, t) d\alpha \\ L'_{2\lambda}(\lambda,t) &= -\overline{L_{2\lambda}(\lambda,t)} \int_{\beta_{D_2}}^{\beta_{D_2}} k'_\lambda(x, y+\beta, z, \lambda, t) d\beta \end{aligned} \quad (8)$$

The covariance of these fluctuation values is:

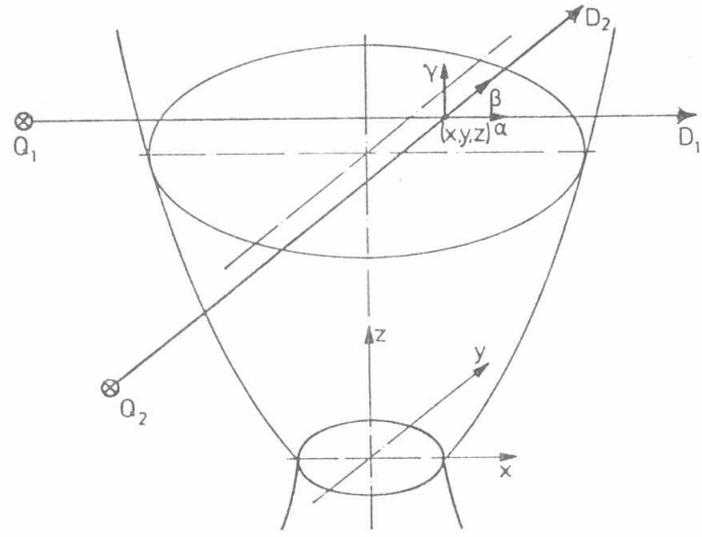


Fig.1. Beams arrangement and coordinates systems for the crossed-beam correlation technique ( Q = laser source, D = detector )

$$G_{\lambda}(x, y, z, \lambda) = \frac{1}{\tau} \int_0^{\tau} L_{1\lambda}(\lambda, t) L_{2\lambda}(\lambda, t) dt \quad (9)$$

From Eqs.(8) and (9):

$$G_{\lambda}(x, y, z, \lambda) = \overline{L_{1\lambda}(\lambda, t) L_{2\lambda}(\lambda, t)} \cdot \int_{\alpha} \int_{\beta} k'_{\lambda}(x+\alpha, y, z, \lambda, t) k'_{\lambda}(x, y+\beta, z, \lambda, t) d\beta d\alpha \quad (10)$$

If the points  $(x+\alpha, y, z)$  and  $(x, y+\beta, z)$  are sufficiently far from each other (i.e. the distance between them is larger than the macrolength of turbulence), then the fluctuations are independent of each other and the covariance will be zero. Only the points within a certain correlation area around the intersection point are affecting the covariance  $G_{\lambda}(x, y, z, \lambda)$ . This means that the covariance  $G_{\lambda}(x, y, z, \lambda)$  contains only information from the correlation area (Diameter  $\approx 2 \times$  macrolength of turbulence, with the intersecting point as the centre). At this point the correlation of both signals has the biggest value, and then this value decreases until reaching zero when going away from the point of intersection.

According to the analysis made by Fisher and Damkevala [4], the integral  $\int_{\alpha} \int_{\beta} k'_{\lambda}(x+\alpha, y, z, \lambda, t) k'_{\lambda}(x, y+\beta, z, \lambda, t) d\beta d\alpha$  represents the fluctuation density of the spectral absorption coefficient  $k'_{\lambda}(x, y, z, \lambda, t)$  multiplied by an integral correlation area  $A_{\lambda}(x, y, z)$ :

$$G_{\lambda}(x, y, z, \lambda) = \overline{L_{1\lambda}(\lambda, t) L_{2\lambda}(\lambda, t)} k'_{\lambda}(x, y, z, \lambda, t) A_{\lambda}(x, y, z) \quad (11)$$

and the integral correlation area  $A_{\lambda}(x, y, z)$  is determined as:

$$A_{\lambda}(x, y, z) = l_{\lambda}(x) l_{\lambda}(y) \quad (12)$$

$l_\lambda(x)$  and  $l_\lambda(y)$  are the radial turbulence scales in  $x$  and  $y$  directions respectively. Under the assumption that these turbulence scales are independent of the radial location in the flow, they can be determined from the following equations [4]:

$$l_\lambda(x) = \frac{\overline{L_{2\lambda}(\lambda, t)}}{\overline{L'_{2\lambda}{}^2(\lambda, t)}} \int \frac{G_\lambda(x, y, z, \lambda)}{L_{1\lambda}(\lambda, t)} dy \quad (13)$$

$$l_\lambda(y) = \frac{\overline{L_{1\lambda}(\lambda, t)}}{\overline{L'_{1\lambda}{}^2(\lambda, t)}} \int \frac{G_\lambda(x, y, z, \lambda)}{L_{2\lambda}(\lambda, t)} dx \quad (14)$$

The fluctuation intensity of the local spectral absorption coefficient in Eq.(11) can, then, be determined as:

$$k_\lambda'^2(x, y, z, \lambda, t) = \frac{\overline{L'_{1\lambda}{}^2(\lambda, t)} \overline{L'_{2\lambda}{}^2(\lambda, t)} \overline{G_\lambda(x, y, z, \lambda)}}{\overline{L_{1\lambda}(\lambda, t)}^2 \overline{L_{2\lambda}(\lambda, t)}^2 \int \frac{G_\lambda(x, y, z, \lambda)}{L_{2\lambda}(\lambda, t)} dx \int \frac{G_\lambda(x, y, z, \lambda)}{L_{1\lambda}(\lambda, t)} dy} \quad (15)$$

#### 4. LOCAL FLUCTUATION VALUES OF TEMPERATURE AND SPECIES CONCENTRATION

With the crossed-beam method using beams having the same wavelength, the time-averaged values cannot be measured. Only the fluctuation values may be determined. The local fluctuation intensities of both temperature and species concentration could be calculated using the value of the fluctuation intensity of the local absorption coefficient which is numerically computable from Eq.(15).

The spectral absorption coefficient  $k_\lambda$  is related to the line absorption coefficient  $k_g$  as:

$$k_\lambda = k_g P_{\lambda, v} \quad (16)$$

where  $P_{\lambda, v}$  is the Voigt-profile function. For a certain spectral absorption line,  $k_g$  is a function of temperature  $T$  and species concentration  $\psi$ , whereas  $P_{\lambda, v}$  is a pure temperature function [5]. Eq.(16) may, then, be written in the following form:

$$k_\lambda = C_g \psi F(T) \quad (17)$$

where  $C_g$  and  $F(T)$  are spectral line constant and temperature function respectively.

The fluctuation value and fluctuation intensity of the spectral absorption coefficient are determined from Eq.(17) as:

$$k_\lambda' = C_g (\overline{F \psi'} + \overline{F' \psi} + \overline{F' \psi'} - \overline{F' \psi}) \quad (18)$$

$$\text{and } k_\lambda'^2 = C_g^2 (\overline{F^2 \psi'^2} + 2 \overline{F F' \psi'^2} + \overline{F'^2 \psi^2} + 2 \overline{\psi F'^2 \psi'} + \overline{F'^2 \psi'^2} - \overline{F' \psi'}^2 + 2 \overline{F' \psi' F \psi}) \quad (19)$$

Neglecting the third and higher order fluctuation terms in Eq. (19),  $k_{\lambda}'^2$  can be simplified as:

$$k_{\lambda}'^2 = C_{\lambda}^2 ( \overline{F^2 \psi'^2} + \overline{F'^2 \psi^2} - \overline{F' \psi'}^2 + 2 \overline{F' \psi' F \psi} ) \quad (20)$$

When the measurements are carried out for a spectral line(a) having  $F_a'(T)=0$  or  $F_a(T)=\overline{F_a(T)}=F_a(\overline{T})$ , then:

$$k_{\lambda, \alpha}'^2 = C_{\lambda, \alpha}^2 \overline{F(T)^2 \psi'^2} \quad (21)$$

and the fluctuation intensity of the concentration  $\overline{\psi'^2}$  can be determined:

$$\overline{\psi'^2} = k_{\lambda, \alpha}'^2 / C_{\lambda, \alpha}^2 \overline{F(T)^2} \quad (22)$$

On the other hand, when the measurements are made for a spectral line(b) having a linear temperature dependence, i.e.:

$$F_b(T) = A_0 + A_1 T \quad (23)$$

where  $A_0$  and  $A_1$  are constants, then fluctuation intensity of the temperature  $\overline{T'^2}$  can be determined as:

$$\overline{T'^2} = \overline{F_b'^2} / A_1^2 \quad (24)$$

However, the fluctuation intensity of the temperature function could be calculated from Eq.(20) by neglecting the correlation  $\overline{F' \psi'}$ .

## 5. CORRELATION OF CROSSED BEAMS HAVING DIFFERENT WAVELENGTHS

The crossed laser beams  $Q_1D_1$  and  $Q_2D_2$  of Fig.1 are considered again, but in this time they have different wavelengths  $\lambda_1$  and  $\lambda_2$ . According to Eq.(10):

$$\frac{G_{\lambda}(x, y, z, \lambda_1, \lambda_2)}{L_{1\lambda}(\lambda_1, t) L_{2\lambda}(\lambda_2, t)} = \int_{\alpha} \int_{\beta} \overline{k_{\lambda}'(x+\alpha, y, z, \lambda_1, t) k_{\lambda}'(x, y+\beta, z, \lambda_2, t)} d\beta d\alpha \quad (25)$$

Krause, Davies and Cann [6] have carried out some experiments from which it may be concluded that the line integrals of Eq. (25) can be approximated to an area integral as follows:

$$\int_{\alpha} \int_{\beta} k_{\lambda}'(x+\alpha, y, z, \lambda_1, t) k_{\lambda}'(x, y+\beta, z, \lambda_2, t) d\beta d\alpha = k_{\lambda}'(x, y, z, \lambda_1, t) \int_{\alpha} \int_{\beta} k_{\lambda}'(x+\alpha, y+\beta, z, \lambda_2, t) d\beta d\alpha \quad (26)$$

The spectral absorption coefficient at the crossing point  $(x, y, z)$  may be given by a Taylor series approximation using the fluctuations of temperature and concentration at this point as follows:

$$\begin{aligned} k_{\lambda}(x, y, z, \lambda_1, t) &= k_{\lambda}(T, \psi, \lambda_1, t) = k_{\lambda}(\overline{T}+T', \overline{\psi}+\psi', \lambda_1, t) \\ &= k_{\lambda}(\overline{T}, \overline{\psi}, \lambda_1) + (T' \frac{\partial}{\partial T} + \psi' \frac{\partial}{\partial \psi}) k_{\lambda}(T, \psi, \lambda_1, T) \Big|_{\substack{T=\overline{T} \\ \psi=\overline{\psi}}} \\ &\quad + \frac{1}{2} (T' \frac{\partial}{\partial T} + \psi' \frac{\partial}{\partial \psi})^2 k_{\lambda}(T, \psi, \lambda_1, t) \Big|_{\substack{T=\overline{T} \\ \psi=\overline{\psi}}} \end{aligned}$$

$$= \overline{k_{\lambda}(\tau, \psi, \lambda_1, t)} + k'_{\lambda}(\tau, \psi, \lambda_1, t) \quad (27)$$

Substituting from Eqs.(26) and (27) into Eq.(25), one gets:

$$\begin{aligned} \frac{G_{\lambda}(x, y, z, \lambda_1, \lambda_2)}{L_{1\lambda}(\lambda_1, t) L_{2\lambda}(\lambda_2, t)} &= \left[ k_{\lambda}(\bar{\tau}, \bar{\psi}, \lambda_1) - \overline{k_{\lambda}(\tau, \psi, \lambda_1, t)} \right] \int_{\alpha} \int_{\beta} \overline{k'_{\lambda}(x+\alpha, y+\beta, z, \lambda_2, t)} d\beta d\alpha \\ &+ \frac{\partial k_{\lambda}(\tau, \psi, \lambda_1, t)}{\partial \tau} \bigg|_{\substack{\tau=\bar{\tau} \\ \psi=\bar{\psi}}} \int_{\alpha} \int_{\beta} \overline{\tau' k'_{\lambda}(x+\alpha, y+\beta, z, \lambda_2, t)} d\beta d\alpha \\ &+ \frac{\partial k_{\lambda}(\tau, \psi, \lambda_1, t)}{\partial \psi} \bigg|_{\substack{\tau=\bar{\tau} \\ \psi=\bar{\psi}}} \int_{\alpha} \int_{\beta} \overline{\psi' k'_{\lambda}(x+\alpha, y+\beta, z, \lambda_2, t)} d\beta d\alpha \\ &+ \frac{1}{2} \frac{\partial^2 k_{\lambda}(\tau, \psi, \lambda_1, t)}{\partial \tau^2} \bigg|_{\substack{\tau=\bar{\tau} \\ \psi=\bar{\psi}}} \int_{\alpha} \int_{\beta} \overline{\tau'^2 k'_{\lambda}(x+\alpha, y+\beta, z, \lambda_2, t)} d\beta d\alpha \\ &+ \frac{\partial^2 k_{\lambda}(\tau, \psi, \lambda_1, t)}{\partial \tau \partial \psi} \bigg|_{\substack{\tau=\bar{\tau} \\ \psi=\bar{\psi}}} \int_{\alpha} \int_{\beta} \overline{\tau' \psi' k'_{\lambda}(x+\alpha, y+\beta, z, \lambda_2, t)} d\beta d\alpha \\ &+ \frac{1}{2} \frac{\partial^2 k_{\lambda}(\tau, \psi, \lambda_1, t)}{\partial \psi^2} \bigg|_{\substack{\tau=\bar{\tau} \\ \psi=\bar{\psi}}} \int_{\alpha} \int_{\beta} \overline{\psi'^2 k'_{\lambda}(x+\alpha, y+\beta, z, \lambda_2, t)} d\beta d\alpha \quad (28) \end{aligned}$$

#### 5. LOCAL TIME-AVERAGED VALUES OF TEMPERATURE AND SPECIES CONCENTRATION

When the measurements are carried out with a wavelength  $\lambda_1$  for a spectral line for which the spectral absorption coefficient is independent of the temperature in the considered temperature range, then the first and second order derivatives of Eq.(28) disappear. Moreover, the second order concentration derivative disappears also because of direct proportionality of spectral absorption coefficient with concentration. Eq.(28) is then simplified as:

$$\frac{G_{\lambda}(x, y, z, \lambda_1, \lambda_2)}{L_{1\lambda}(\lambda_1, t) L_{2\lambda}(\lambda_2, t)} = D_{\lambda}(\lambda_1, \lambda_2) = \frac{\partial k_{\lambda}(\tau, \psi, \lambda_1, t)}{\partial \psi} \bigg|_{\substack{\tau=\bar{\tau} \\ \psi=\bar{\psi}}} \int_{\alpha} \int_{\beta} \overline{\psi' k'_{\lambda}(x+\alpha, y+\beta, z, \lambda_2, t)} d\beta d\alpha \quad (29)$$

The left-hand side of Eq.(29) is experimentally determinable, and by differentiation:

$$D_{\lambda}(\lambda_1, \lambda_2) = \frac{k_{\lambda}(\bar{\tau}, \bar{\psi}, \lambda_1)}{\bar{\psi}} Q_{\psi} \quad (30)$$

with the wavelength( $\lambda_2$ )-dependent term:

$$Q_{\psi} = \int_{\alpha} \int_{\beta} \overline{\psi' k'_{\lambda}(x+\alpha, y+\beta, z, \lambda_2, t)} d\beta d\alpha \quad (31)$$

If two experiments are made with  $\lambda_1 = \lambda'_1$  and  $\lambda_1 = \lambda''_1$  and keeping  $\lambda_2$  constant, then the time-averaged value of the temperature  $\bar{\tau}$  can be determined from the equation:

$$\frac{D_{\lambda}(\lambda'_1, \lambda_2)}{D_{\lambda}(\lambda''_1, \lambda_2)} = \frac{k_{\lambda}(\bar{\tau}, \bar{\psi}, \lambda'_1)}{k_{\lambda}(\bar{\tau}, \bar{\psi}, \lambda''_1)} \quad (32)$$

The time-averaged value of concentration cannot be obtained

using this analysis because of the direct proportionality of spectral absorption coefficient with  $\psi$ . However, this average value is determinable using the one-beam laser spectroscopy in axisymmetrical turbulent flames [2].

## 6. SPECTRAL LINES OF EXPERIMENTAL INTEREST

The unstable components (or radicals) formed in flames are of great importance for understanding reaction mechanisms. OH-radical is one of the important species present in most combustion processes.

The crossed-beam correlation method can be used for determination of OH-concentration and temperature profiles in turbulent hydrocarbon/air flames. Application of this method requires that the measurements have to be carried out for spectral lines having special relations between spectral absorption coefficient and temperature. To achieve the maximum absorption, such measurements should be made at the central wavelength ( $\lambda_0$ ) of the chosen spectral line.

The dependence of the spectral absorption coefficient at the central wavelength ( $k_{\lambda_0}$ ) on temperature has been studied for different spectral lines of OH-radical. The spectral lines of 1-0 band of  $^2\Sigma - ^2\Pi$  system was chosen because this range of wavelength (near 2800 Å) is suitable for absorption measurements in the ultraviolet region by tunable dye lasers.

Fig.2 shows the relation between  $k_{\lambda_0}$  and  $\tau$  for three spectral lines (P<sub>25</sub>, P<sub>18</sub> and Q<sub>112</sub>) in different temperature ranges covering the temperature values expected in most hydrocarbon/air turbulent flames. Each spectral line has an approximately constant  $k_{\lambda_0}$  with respect to temperature in a certain temperature range with a maximum error given in Table 1.

Table 1 Spectral lines having approximately constant  $k_{\lambda_0}$  with respect to T

Line	Central Wavelength (Å)	Temperature Range (°K)	Maximum Error (%)
P <sub>25</sub>	2844.75	375 - 675	< ±5
P <sub>18</sub>	2855.86	675 - 1310	< ±7
Q <sub>112</sub>	2852.66	1310 - 2400	< ±7

Moreover, Fig.3 gives the relation between  $k_{\lambda_0}/\psi$  and T for the spectral line P<sub>18</sub> in the temperature range 300-2500 °K. This relation can be approximately linearized in different temperature ranges as illustrated in Fig.3. These linear relations have the general form:  $k_{\lambda_0}/\psi = A_0 + A_1 T$  where  $A_0$  and  $A_1$  are constants. These constants are given in Table 2.

Table 2 Data of P<sub>18</sub>-spectral line

Temperature Range (°K)	$A_0$ (cm <sup>-1</sup> )	$A_1$ (cm K) <sup>-1</sup>	Maximum Error (%)
300- 640	- 42.4	0.168	< ±2
640- 900	28.7	0.0569	< ±3.5
900-2500	110.1	-0.0335	< ±7

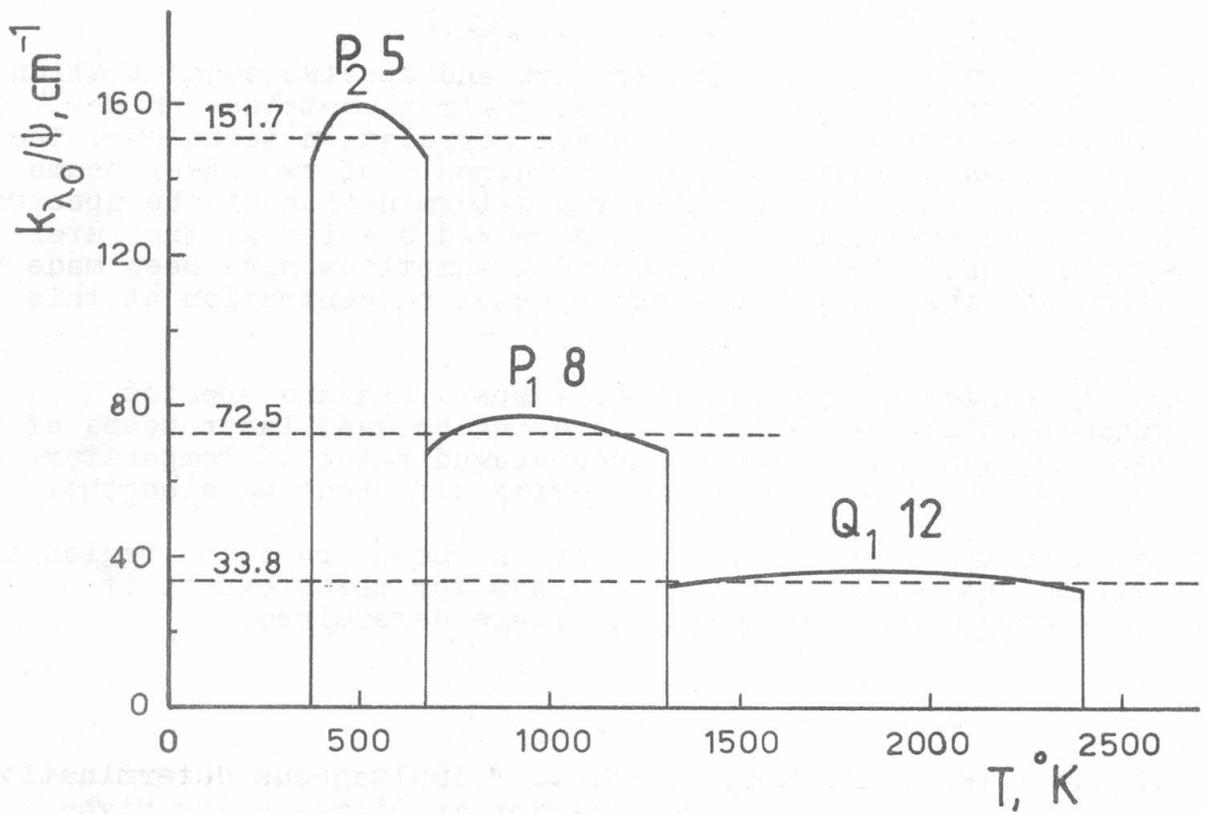


Fig. 2. OH-spectral lines having approximately constant absorption coefficient w.r.t. temperature

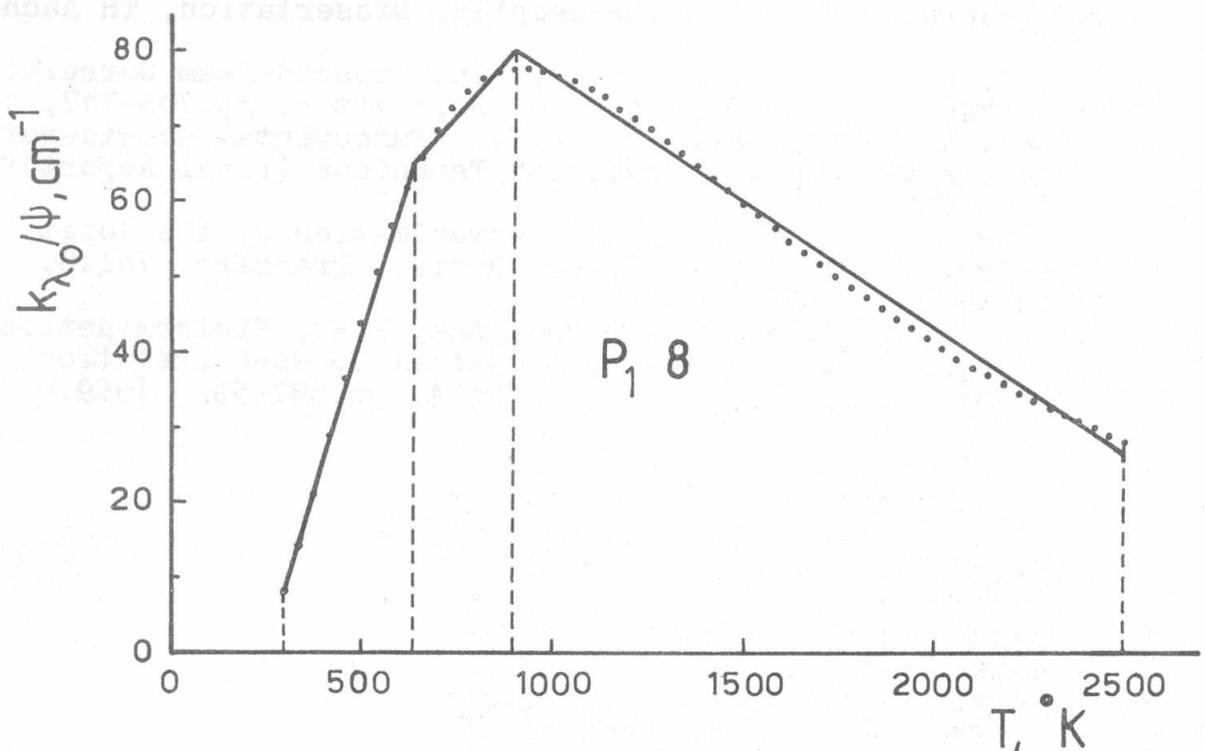


Fig. 3. Linear temperature dependence of absorption coefficient of  $P_1 8$  - spectral line of OH-radical

## 7. CONCLUSIONS

It has been shown that temperature and species concentration in turbulent flames-irrespective of their geometries-can be determined using the crossed-beam correlation technique. The correlation between the received signals of two laser beams crossed in the flame enables the determination of the spectral absorption coefficient of the measured species at the intersection point. Then, a number of assumptions have been made to calculate the temperature and species concentration at this point.

The fluctuation intensities of temperature and species concentration are determinable using crossed laser beams of the same wavelength, whereas time-averaged value of temperature can be obtained with laser beams having different wavelengths.

The spectral lines of OH-radical in the ultraviolet region are studied and suitable spectral lines for measurements of temperature and OH-concentration are determined.

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## NOMENCLATURE

$A_\lambda$	Integral correlation area
$b$	Flame width
$C_\lambda$	Spectral line constant
$F$	Temperature function
$G_\lambda$	Covariance of fluctuation values
$k_\lambda$	Spectral absorption coefficient
$k_\lambda$	Line absorption coefficient
$\ell_\lambda$	Radial turbulence scale

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$L_\lambda$  Spectral radiation density  
 $P_{\lambda,\nu}$  Voigt-profile function  
 $t$  Time coordinate  
 $T$  Temperature  
 $x,y\&z$  Length coordinates

## Greek Letters:

$\alpha,\beta\&\gamma$  Length coordinates  
 $\lambda$  Wavelength  
 $\tau$  Time interval  
 $\psi$  Species concentration

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