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LINE REVERSAL GAS FLOW TEMPERATURE MEASUREMENTS: EVALUATIONS OF THE OPTICAL ARRANGEMENTS FOR THE INSTRUMENT

Yu.A. Gorshkov, V.I. Vladimirov

ABSTRACT:
The line reversal technique, due to comparative simplicity of optical arrangement and high accuracy of line-of-sight mean temperature measurement, will probably for a long time remain the most effective technique for temperature measurement of practical high temperature gas flows.

However, in field conditions even this technique becomes very sensitive to optical misalignments and fouling of optical port diameters and the second - vice versa. This may give raise to trade-offs in design solutions. This problem is of spectral importance for particle-laden flow in coal-fired facilities. In different laboratories much attention was drawn upon the development of line-reversal theory and instruments. However, the optical schematic of the instrument can be further optimized in order to fit properly the given geometry of duct. In this work two problems of this kind have been considered:

FIRST PROBLEM - selection of optimum schematic parameters for a given geometric factor (etendue) of spectral instrument. This optimum corresponds to minimum diameter of optical ports required for measurements.

SECOND PROBLEM - selection of optimum schematic for given maximum allowable diameters of optical ports limited by the danger of their contamination. In this case the optimum corresponds to maximum value of radiation flux to enter the monochromator. The solutions are given to calculate the parameters of optimum arrangements.

The solution is obtained for practical case of equal diameters of the two optical ports required for measurements, however, it can be easily extended to more general case.

In addition, it is shown that the two widely used classical optical arrangements - where the image of the filament of the calibrated lamp is placed in the center of the flame region or both the filament and the monochromator entrance slit are placed in the focal planes of adjacent lenses - do not meet the optimum conditions.

KEYWORDS:
temperature measurement, optical measurement
gas spectral optimum

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LINE REVERSAL GAS FLOW TEMPERATURE MEASUREMENTS:
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1. INTRODUCTION

Probe techniques for hot gas flow temperature measurements are often ineffective at about 1500 °C, particularly in field conditions. At higher temperatures the spectral techniques based on the temperature dependency of the thermal radiation are more promising. At temperatures below 3000 °C where reliable calibrated radiation sources are available, the most accurate means to determine the gas-flow temperature is probably the line-reversal technique. The technique is based on direct determination of the spectral emissivity (e) and the temperature in terms of two optical signals recorded using the same detector - the gas-flow radiancy and the attenuation factor for a calibrated external source radiancy passing across the gas-flow. Consequently, the effect of uncertainty and instability in the flow emissivity, which is the main source of error inherent in optical temperature measurements, is greatly reduced. In a few cases reported in literature [1] the measurement error did not exceed 1-2%. The line-reversal technique and its various modifications have been widely used to determine flow temperatures in the experiments with laboratory flames [2, 3, 4] and shock tubes [6, 7]. The applications of this technique to practical high temperature combustion flows, where intrusive measurements are not possible, are also known. These are rocket exhausts [5], gas dynamic lasers [8] and various MHD gas- and coal-fired facilities in USSR [1, 9, 10], India [11], USA [12-14], Japan [15], and China [16].

The use of a reference light source situated behind the flow somehow complicate the optical arrangement of the line-reversal instrument. This is especially cozzed in field conditions and/or in "closed-flow" facilities (e.g. combustion chambers and shock tubes) where the smaller diameters of optical ports, and long pipes separating windows from the free stream, are required to prevent the fouling and damage of the windows. On the other hand it is essential to provide sufficiently large aperture for radiances recorded, the required aperture stop diameter, increasing with the increase of the wavelength used for the measurements.

The recommendations to improve the line-reversal, optical arrangement in order to fit the shape of the
optical ports, or vice-versa to select the dimensions of the ports required for line-reversal temperature measurements can be found in a number of publications, however it is felt that the problem still persists. The recommendations presented in [17] are based on assumption of uniform distribution of light intensity in the arbitrary cross section of light beam formed by receiving optics near the entrance detector slit and therefore inaccurate. F. Linn [10] has developed the model to calculate the minimum allowable diameter of the detector-side window and/or its optimum axial position. The authors of this present paper have recently used similar, however, somehow more general approach to evaluate the optimum parameters for line-reversal optical arrangement [18]. Two problems have been considered:

- determination of the optical arrangement parameters for the maximum aperture at fixed diameters of detector-side and source-side windows of the facility and distance between the windows (Problem B in [18]);
- determination of the optical arrangement to provide the use of the smallest possible optical windows in a facility at a given geometric factor of the spectral detector (Problem A in [18]).

Below the results obtained in [18] are presented in more details to provide more convenience for their practical use and two practical examples of line-reversal optical arrangement are considered. Several small misprints occurred in [18] have been corrected.

2. LINE-REVERSAL MEASUREMENT PROCEDURE AND OPTICAL ARRANGEMENT OF THE INSTRUMENT

Figure 1 illustrates the optical arrangement of the line-reversal temperature measurement.

The radiancy from a gas-flow region takes a focus on the spectral detector entrance slit using the lens S, while the radiancy from the calibrated source takes the focus in the gas region on the detector slit. The diameters of the detector-side window d_s and lamp-side window d_l should be large enough so as not to restrict the optical beam formed by the aperture stop specified below. Using the spectral detector the radiant fluxes emitted by the gas flow with and without a calibrated source are derived together with the pre-flow radiant flux of the source:

\[
F_f = K_s C_f B(T_f) [1 - \exp(-\tau)] \Delta \lambda ,
\]  

(1)
source-on flux

\[ F_{fl} = F_f + K_f K_s G_f B(T_f) \exp(-\tau) \Delta \lambda, \]

(2)

pre-flow source

\[ F_l = K_f K_s G_f B(T_f) \Delta \lambda, \]

(3)

where \( K_f, K_s \) are transmissivities of the source-side and detector-side windows, \( T_f \) is calibrated brightness temperature of the source, \( T_f \) is gas-flow temperature, \( \tau \) the optical depth of the gas flow along the line-of-sight in the spectral interval \( \Delta \lambda \) (the latter is assumed to be essentially narrow compared to the half-width of the spectral line used for measurements), \( B(T) \) is the Plank function for a black body at wavelength \( \lambda \). \( G_f \) and \( G_l \) are geometric factors (etendue) that restricts the radiant fluxes to enter the slit. Equations (1) - (3) yield the measured flame temperature in terms of recorded radiant fluxes:

\[ T_f = \left[ \frac{1}{T_f} - \frac{\lambda}{C_2} \ln \left( K_f \cdot \frac{G_e}{G_f} \cdot \frac{F_f}{F_f + F_l - F_{fl}} \right) \right]^{-1}. \]

(4)

In the arrangement shown in the figure 1 \( G_f = G_l \). In most line-reversal instruments both \( F_f \) and \( F_{fl} \) are restricted by the same aperture stop in order to eliminate the errors caused by uncertainty in \( G \) values, consequently

\[ G_f = G_l = G \]

(5)

(the instrument with \( G_f > G_l \) has been used in [19].)

In this work the detector entrance slit is assumed a circular tip of the light collection fiber \( h_s \) in diameter. The aperture stop for the radiation entering the slit is the frame of the lens \( S \) (as shown in figure 1). In this case the geometric factor is given by
where $D_s$ is diameter of the lens $S$, $S_s$ the distance between the lens and the fiber tip,

$$
tg\theta = \frac{D_s}{2S_s}.
$$

If $\theta$ is greater than defined below maximum angle $\alpha^*$ of the fiber (34) the geometric

factor should be defined in terms of $\alpha^*$:

$$
G = \frac{\pi^2 h_s^2}{4} \text{tg}^2\theta^*.
$$

The dimension of the optical arrangement shown in fig. 1 should obey the following formulae:

$$
D_s = h_s + 2\theta S_s,
$$

$$
h_s^1 = h_s \frac{1 + \omega_\lambda}{S_s} = h_s \frac{1 + H - \omega_\lambda}{S_s},
$$

$$
d_s \geq h_s^1 + \frac{\omega_\lambda}{\frac{1}{S_s} + \omega_\lambda} (D_s - h_s^1),
$$

$$
d_i \geq (D_s + h_s^1) \frac{1 + H}{\frac{1}{S_s} + \omega_\lambda} - D_s.
$$
where $h_s$ is the diameter of the entrance slit image formed by lens $S$. Below the optical arrangements are considered in terms of minimum allowable diameters of all the stops, which obey the eqs. (9) - (10) with sign of equality. The dimensions $H, l_s, l, l_e, \omega_s, \omega_e$ are defined in figure 1.

Note that the angles $\theta_s$ and $\theta$ are not equal to each other. The former is defined in eq. (7):

$$
\theta_s = \frac{D_s - h_s}{2 \, S_s},
$$

and the latter is defined by

$$
\theta = \frac{D_s}{2 \, S_s},
$$

3. THE OPTICAL ARRANGEMENT PROVIDING MAXIMUM $G$ FOR GIVEN DIAMETERS $d_s$ AND $d_e$ OF A FACILITY WINDOW AND THE DISTANCE $H$ (PROBLEM B IN [18])

Consider a high temperature facility, where the gas-flow temperature is to be measured, with the maximum allowable optical ports diameter $d$ and the minimum allowable distance between the windows $H$.

3.1. The crossed beam optical arrangement

The image of the detector entrance slit is formed in this case by the lens $S$ in the middle of the gas flow. The distance from the image plane to the detector-side window and source-side window are $\omega_s$ and $\omega_e$, respectively ($\omega_1 + \omega_s = H$). In the standard crossed-beam arrangement

$$
D_f \geq (D_s + h_s^1) \frac{l_s + H + l_e}{l_s + W_s} - D_s,
$$

(11)
as shown in fig. 2.

Substituting eq. (8) into the geometric factor equation (6) we obtain

\[
G = \frac{\pi^2}{16} \cdot \frac{h_s^1 D_s^2}{(l_s + 0.5 H)^2}.
\]  

(13)

Using eqs. (9), (10) and (12) we may express \(h_s^1\) and \(D_s\) in terms of \(d_s\) and \(d_l\):

\[
h_s^1 = (d_l - d_s) \frac{l_s + 0.5 H}{H},
\]

(14)

\[
D_s = d_s \frac{l_s + 0.5 H}{0.5 H} - (d_l - d_s) \frac{l_s(l_s + 0.5 H)}{0.5 H^2}.
\]

(15)

Consequently, eqs. (14), (15) can be used to express \(G\) in terms of \(d_s\), \(d_l\) and \(H\):

\[
G = \frac{\pi^2}{16 H^2} \left(1 + \frac{2 l_s}{H}\right)^2 \left\{ (d_l - d_s) \left[ d_s \left(1 + \frac{l_s}{H}\right) - d_l \frac{l_s}{H} \right] \right\}.
\]

(16)

Combining eqs. (9) and (10) yields:

\[
\omega_s = \omega_l = \frac{H}{2}.
\]
\[ d_l - d_s = h_s \frac{H}{1_s + 0.5H}. \]  

Eq. (17) shows, that the diameter of the source-side window \(d_l\) for the crossed beam arrangement should always exceed \(d_s\). Differentiation of eq. (16) with respect to \(d_s\) at \(d_l = d = \text{const}\) yields the value of \(d_s\) at which \(G = G_{\text{max}}\) for given facility configuration:

\[ d_s = \frac{d}{2} \left[ \frac{1 + \frac{21_s}{H}}{1 + \frac{1_s}{H}} \right]. \]  

Respectively,

\[ G_{\text{max}} = \frac{\pi d^4}{25GH^2} \cdot \left( \frac{1 + \frac{21_s}{H}}{1 + \frac{1_s}{H}} \right)^2. \]  

Substituting the eq. (18) at \(d_l = d\) in eqs. (7) - (11) yields the dimension of the optical line-reversal arrangement with \(G_{\text{max}}\) at given diameters of the windows and the distance separating the windows

\[ D_s = 0.5 \ d \left( 1 + \frac{21_s}{H} \right), \]  

\[ h_s = s_s \left[ \frac{d}{2H} \cdot \frac{1}{1 + \frac{1_s}{H}} \right], \]  

\[ s_s = \frac{d}{2H} \left[ \frac{1}{1 + \frac{1_s}{H}} \right]. \]
\[
\theta_s = \frac{d}{4} \left[ \frac{1 + \frac{2l_s}{H}}{S_s} - \frac{1}{1 + \frac{l_s}{H}} \right], \quad (22)
\]

\[
D_l = d + d \frac{l_l}{H} \left( 1 + \frac{1}{2(1 + \frac{l_s}{H})} \right), \quad (23)
\]

\[
h_s^1 = \frac{d}{4} \cdot \frac{1 + \frac{2l_s}{H}}{1 + \frac{l_s}{H}}. \quad (24)
\]

### 3.2. The parallel beam arrangement

Often the line-reversal Instrumen the detector slit is positioned in the focal point of the lens S and the calibrated source - in the focal point of the lens I as shown in fig. 3, whereby the image plane is removed from the gas flow. The maximum detector slit diameter limited by the condition (5) is related to the other parameters by the equations:

\[
\frac{h_s}{f_s} = \frac{d_s - D_s}{1_s} = \frac{d_s - D_s}{1_s + H} = \frac{D_s - D_s}{1_s + H + 1_l}. \quad (25)
\]

The equation for G is obtained by substitution \( S_s = f_s \) in (6):
The eq. (25) yields

\[ D_s = d_s - (d_e - d_s) \frac{1_s}{H} \cdot \]

and

\[ h_s = d_s \frac{d_s}{d_e - d_s} \frac{1_s}{H} \cdot \]

Using these in (26) we obtain:

\[ G = \frac{\pi^2}{16} h_s D_s^2 \frac{\pi^2}{16} (d_s - d_i)^2 \frac{2}{H^2} \frac{d_s}{d_s - (d_i - d_s) \frac{1_s}{H}} \cdot \]

Differentiating \( G \) in respect to \( d_s \) at \( d_i = d_s = \text{const} \) yields the equation for \( d_s \) corresponding to \( G_{\text{max}} \) which is similar to (18)

\[ d_s = \frac{1}{2} d \frac{1 + \frac{2 1_s}{H}}{1 + \frac{1_s}{H}} \cdot \]

and respective formula for \( G_{\text{max}} \)
Substitution of eq. (27) into (25) yields at \( d_e = d \) the parameters of optical line-reversal arrangement which has maximum \( G \) at given \( d_e, d_s \) and \( H \):

\[
D = 0.5 \, d
\]  
(29)

\[
\frac{h_s}{f_s} = 0.5 \, d \frac{1}{1_s + H}
\]  
(30)

\[
D_e = d + d \frac{1}{2 \, H} \cdot \frac{1}{1 + \frac{1_s}{H}}
\]  
(31)

Note that the maximum allowable window diameters \( d_s \) at \( G_{\text{max}} \) obtained above for crossed beam (18) with parallel beam (27) arrangements coincides, however the former \( G_{\text{max}} \) value is greater by factor of \((1 + 2 \, l_s / H)^2\).

Note also that \( d_s \) values (18) and (27) are substantially less than window diameter \( d \):

\[
d_s = 0.5 \, d
\]

This limitation is due to condition (5). However in a facility with equal diameters of the windows it greatly reduces the maximum allowable \( G \) and consequently the radiances to be measured. In such a facility it would be more natural to use the total area of both windows, whereas the geometric factor would be equal to
whereas $G_f$ is given by (19) and (28).

\[ G_f = \frac{\pi_2 d_4}{16 H^2}, \]  

which is almost 16 lines greater than $G_{\text{max}}$ as given by (19) and (28).
4. SELECTION OF LINE-REVERSAL OPTICAL ARRANGEMENT TO PROVIDE THE USE OF THE SMALLEST OPTICAL PORTS AT GIVEN GEOMETRIC FACTOR SPECTRAL DETECTOR

(Problem A in [18])

Let the geometric factor of the spectral detector be constant and equal to (6a):

\[ G_d = \frac{\pi^2 h_s^2}{4} \tan^2 \theta \] (33)

Since entrance slit of the detector is circular tip of the light-collection fiber, \( h_s \) in diameter, \( \theta \) represents the maximum allowable angle for the fiber \( \theta^* \), defined as [20, 21]:

\[ \theta^* = \arcsin \left( \frac{3}{n_o} \sqrt{n_k^2 - \frac{12}{n_m^2}} \right) \] (34)

where \( n_o, n_k, \) and \( n_m \) are refractive indexes of air, core of the fiber and its shell,

\[ A_y = \sqrt{\int_k^2 - \int_m^2} \] is termed the numerical aperture of the fiber. The optical arrangement is shown in figure 1, the limiting values of the arrangement are related to each other by the eqs. (7) - (11). In order to determine the limiting diameters of the optical windows of the facility for given \( G_d \) we substitute \( h_s \) (8) in eq. (10):

\[ d_1 = \left[ D_s + \frac{h_s}{S_s} (1_s + H - \omega_b) \right] \frac{1_s + H}{1_s + H - \omega_b} - D_s \] (35)

Differentiation of (35) with respect to \( \omega_b \), at constant \( G_d \), i.e. at constant \( D_s, h_s, \) and \( S_s \), yields:
As this derivative is always positive, one may conclude that minimum allowable lamp-side window diameter $d_i$ increases with the increase of $\omega_\varphi$ whereby the opportunity appears to reduce $d_i$ at constant $G_d$ by removing the slit image plane from its standard position $\omega_i = \omega_s = H/2$ closer to the lamp. The probable useful solution is $\omega = 0$, whereby the slit image is positioned into the plane of the lamp-side window. At $\omega_i = 0$ the eq. (35) reduces to

$$d_i = h_s \frac{H + l_s}{S_s}. \quad (36)$$

(The obvious requirement which is to be fulfilled in this case is $d_i = h_i$.) The opposite side window diameter $d_s$ is obtained by using $\omega_i = 0$ in eqs. (7) (9):

$$d_s = h_s \frac{l_s + H}{S_s} + \left[D_s - h_s \frac{l_s + H}{S_s}\right] \frac{H}{l_s + H}. \quad (37)$$

Using $D_s$ as obtained from eq. (6) and (36) permits to write down the equation interrelating $d_s$ and $d_i$ at fixed values of geometric factor of the instrument $G_d$ and the facility dimensions $H$ and $H$.

$$d_s = d_i \frac{l_s}{l_s + H} + \frac{4}{\pi} \sqrt{G_d} \frac{H}{d_i}. \quad (38)$$

Figure 4 shows that diameter of one of the windows may be reduced at simultaneous increase of the other at constant $G_d$. Two specific cases are considered below.

4.1. Minimum window diameter of the detector side

In some cases it may be required to have the narrow window only at the detector side with the given $G_d$ (similar problem for the line-reversal optical arrangement with $\omega_i = \omega_s = H/2$ is discussed in [16].) Differentiating (38) with respect to $d_i$ at constant $G_d$ yields:
Equating (39) to zero yield the value corresponding to minimum $d_s$:

$$d_s = \frac{1_s}{1_s + H} - \frac{4}{\pi} \sqrt{\frac{G \cdot H}{d_s^2}}. \quad (39)$$

Substituting (40) into (38) yields

$$d_s (d_s^{\min}) = \sqrt{\frac{4}{\pi} \sqrt{\frac{G \cdot H}{d_s}} \cdot \frac{H}{1_s} \cdot (1_s + H)}. \quad (40)$$

Substituting (40) into (38) yields

$$d_s^{\min} = 2 \sqrt{\frac{4}{\pi} \sqrt{\frac{G \cdot H}{d_s}} \cdot \frac{H}{1_s + H} \cdot 1_s}. \quad (41)$$

From (36) we obtain

$$S_s (d_s^{\min}) = h_s \cdot \sqrt{\frac{\pi}{4} \frac{1_s (1_s + H)}{\sqrt{G \cdot d \cdot H}}} \quad (42)$$

and from (6)

$$D_s (d_s^{\min}) = \sqrt{\frac{4}{\pi} \sqrt{\frac{G \cdot d}{H}} \cdot \frac{1_s}{H} \cdot (1_s + H)}. \quad (43)$$

Note that in the case of line-reversal temperature measurement in "open" flames, in the above equations one should use

$$l_f = 0; \ l_s = 0; \ d_s = D_s; \ d_s = D_s,$$
where by, as can be seen from eq. (38), the function $D_s$ does not have any minimum.

The $d_i$ and $d_s$ values calculated using (40) and (41) and shown in Table 1 indicate that lamp-side window diameter corresponding to minimum diameter of the detector-side window turns out to be too large. (It also can be seen in figure 4). Therefore it is of interesting to consider the other specific case, i.e. the arrangement with $d_i = d_s$ at given $G_s = $ const.

4.2. The line-reversal optical arrangement with $d_i = d_s$

Combining eqs. (37) and (36) we obtain

$$d_s = d_l + H(D_s - d_l) (H + l_s) . \quad (44)$$

This equation indicates that at $\omega_i = 0$ the arrangement can be constructed with $d_i = d_s = D_s$ i.e. with the minimum allowable diameters of the three main stops equal to each other. The parameters of this arrangement which we will refer to below as "optimum" are found below. The eq. (38) for this case yields:

$$d_{s \text{opt}} = d_s = d_l = D_s = \sqrt{\frac{4}{\pi} \sqrt{G_d} (1_s + H)} \quad (45)$$

and (36) yields

$$S_{s \text{opt}} = \pi \frac{(1_s + H)}{\sqrt{\frac{4}{\pi} \sqrt{G_d}}} , \quad (46)$$

consequently, eq. (11) gives

$$D_{l \text{opt}} = d_{s \text{opt}} (1 + \frac{2}{1_s + H}) . \quad (47)$$
The solution of the "Problem A" obtained above has led to the eq. (38) which yields $d_s$ in terms of $d_t$ and can be used to match the detector having the geometric factor $G_d$ with the dimensions of the facility containing the radiating volume. The peculiarity of the constructed optical arrangement is the position of the detector-slit image into the plane of the source-side window. The latter makes it possible to select the minimum allowable diameters of both windows and the detector-side lens equal to each other thus forming the cylindrical optical path.

For a facility vehicle has the optical ports with a diameter of the geometric factor for the "optimum" line-reversal arrangement may be as large as

$$G_{f, \text{opt}} = \frac{\pi^2}{16} \cdot \frac{D_s^2 (h_s^2)}{(H + l_s^2)^2} = \frac{\pi^2 d^4}{16 (H + l_s^2)^2}.$$  \quad (48)

Comparison of $G_{f, \text{opt}}$ with "maximum geometric factor" defined in (32) indicates that the optimum arrangement effectively uses the total cross sectional area of optical ports, the $G_{f, \text{opt}}$ being almost 16 times larger than maximum allowable G values for both "crossed beam" (19) and "parallel beam arrangements" (28).

Concluding we have to mention the fact that the relations obtained above yield merely the limiting cross sectional dimensions for an optical arrangement. In practice it is convenient to select at first the aperture stop for the radiancy entering the detector. This can be the iris diaphragm adjacent to lens $S$, the detector fiber with maximum allowable angle $e^*$ or the detector aperture may be determined by the aperture ratio of the detector itself. The cross sectional dimensions of all the other elements must be taken somewhat greater than their calculated values to compensate for possible misalignments. (The parameters of the illuminating part of the line-reversal arrangement are calculated below in Appendix 2 for particular examples).
Table 1. The example calculation of line-reversal optical schematic parameters for

\[ H = 224 \text{ mm; } l_s = 10 \text{ mm; } h_s = 0.2 \text{ mm; } G_d = 0.003 \text{ mm}^2 \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>The &quot;minimum d_s case&quot; (section 4.1.)</th>
<th>The &quot;optimum case&quot; (section 4.2.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_s )</td>
<td>eq. calculated value</td>
<td>eq. calculated value</td>
</tr>
<tr>
<td></td>
<td>42 2.4 mm</td>
<td>46 11.6 mm</td>
</tr>
<tr>
<td>( D_s )</td>
<td>43 0.85 mm</td>
<td>45 4.0 mm</td>
</tr>
<tr>
<td>( d_s )</td>
<td>41 1.6 mm</td>
<td>-- 4.0 mm</td>
</tr>
<tr>
<td>( d_l )</td>
<td>40 19.1 mm</td>
<td>-- 4.0 mm</td>
</tr>
</tbody>
</table>
A.1.2. The crossed beam arrangement:

An optical beam pattern in the flame region

Consider the distribution of the local solid angles in the flame volume. For simplicity the entrance slit of the monochromator is assumed to be a circle of diameter $h_s$ and the parameters of the flame (temperature, density of emitters etc.) are assumed constant in the planes rectangular to optical axis of the instrument.

Figure A1 shows the axisymmetric beam pattern in a flame region. The ref. source projecting part of the layout is not shown. At the distances $x'_s$ and $C_s$ respectively one may see the slit and its image in a flame. The diameter of the slit image is equal to

$$h'_s = h_s \frac{C_s}{x'_s}.$$

(In many bench-scale measurements one used

$$h'_s = h_s$$

however, for larger values of $C_s$ the condition

$$h'_s = (5 + 10) h_s$$

is more practical).

It is apparent that only rays, passing both within the lens $s$ and the slit image $h'_s$ will reach the slit thus forming a circular boundary of the beam in the flame region. At distance $x$ from the lens the "total" diameter of the beam is:
APPENDIX 1

THE CONTRIBUTIONS OF DIFFERENT FLAME REGIONS INTO THE LINE-OF-SIGHT LUMINOSITY

A.1.1. Introduction

The line-reversal technique inherently yields the flame temperature based on the line-of-sight average luminosity and optical density measurements. Most of practical flames and hot gas flows are subject to inhomogeneities such as cold boundary layers, and/or fluctuations which are in some way averaged over the flame region, and auxiliary considerations are required to permit the correlation of the inhomogeneities and fluctuations, with the measurement results.

Apparently, such consideration must include the evaluation of the contributions of different flame regions into total measured flux. The contribution of an individual volume element $dV$ is proportional to the solid angle having its vertex on this element and restricting the radiation entering the monochromator slit. The three-dimensional picture of solid angle distributions along and the optical path is considered below in terms of optical parameters.
\[
\frac{D_s(C_s - x) + xh_s'}{2 C_s}, \quad D \leq x \leq C_s \\
\]

\[
R_s = \frac{D_s(x-C_s) + xh_s'}{2 C_s}, \quad x \geq C_s \\
\]

The distribution of the local solid angles in typical beam cross sections I-VI is shown in the lower part of the figure A.1. In the cross section I, coinciding with the plane of the slit image, the solid angle for all the points is constant:

\[
\Omega_1 = \frac{\pi D_s^2}{4 C_s^2} \Omega_1 \\
\]

and uniform within the circular area \( r < R_u \) defined below. In the peripheral area of the beam \( R_u < r < R_e \), say, point \( A' \) the local solid angles is partly blocked (vignetted) by the slit image as shown in the Fig. A1 and decrease with \( r \), reaching zero at \( r = R_e \).

In the cross sections II and V as may be seen in Fig. A1 local solid angle is variable due to vignetting in all the cross sections of the beam (i.e. \( R_u = 0 \)). At the beam axis in this cross section the solid angle is suspended.

Simultaneously by the slit and the frame of the lens, both being the aperture stop, whereas \( \Omega_{II} \) is the highest solid angle value in the flame region:

\[
\Omega_{II} = \frac{\pi}{4} \cdot \frac{D_s^2}{X^2} = \frac{\pi}{4} \cdot \frac{h'_s}{(C_s - x_{II})^2} \\
\]
In the cross sections III, IV, VI the solid angle is uniform in central area \( r < R_u \), whereas unlike (A2), (A3) it is suspended by the slit which in this case is aperture stop, i.e.:

\[
\Omega_{III} = \frac{\pi}{4} \cdot \frac{h_s^{'1/2}}{(C_s - X)^2} .
\]  

(A5)

The radius of uniform cross sectional region of the beam at the distance \( X \) from the lens \( S \) may be shown to be:

\[
\frac{D_s (C_s - X) - X h_s^{'}}{2 C_s} , \quad 0 \leq X \leq C_s
\]

(A6)

\[
\frac{D_s (X - C_s) - X h_s^{'}}{2 C_s} , \quad C_s \leq X .
\]
The eqs. (A1), (A6) readily yield the width of peripheral inhomogeneous (vignetted) portion of the beam:

\[ \frac{X h_s'}{C_s}, \quad 0 \leq X \leq X_0 = \frac{C_s D_s}{D_s + h_s'}; \]

\[ \frac{D_s (C_s - X)}{C_s}, \quad X_0 \leq X \leq C_s; \]

\[ R_t - R_u = \]

\[ \frac{D_s (X - C_s)}{C_s}, \quad C_s \leq X \leq X_1 = \frac{C_s h_s'}{D_s - h_s'}; \]

\[ \frac{X h_s'}{C_s}, \quad X_1 \leq X. \]
A.1.3. The parallel beam arrangement:
An optical beam pattern in the flame region

In this case the plane of the slit image is removed from the flame (see Fig. 3) and it is convenient to start the consideration of the beam from conjugate area adjacent to the slit. Let the plane \( l' \) be conjugate to the plane \( l \) in the flame (simplicity the distance \( X' \) on the Fig. A2 has been chosen is equal to doubled focal distance \( f \) of the lens). Using the simple approach similar to that used in section A.1.2 it can be shown that only the central region of the plane \( I'(r < \frac{R'_u}{2}) \) is illuminated by the flame uniformly. The solid angle having the vertex at a point \( a \) within this area is subtended by the slit, which plays the role of aperture stop for flame radiation

\[
\Omega_1 = 0.25 \pi \frac{h_s^2}{Z^2},
\]

where \( Z \) is the distance from the slit to the flame \( l' \). In the peripheral area of the beam \( R_u < r < R_t \) the luminance gradually decrease with the increase of \( r \) due to vignetting effect.

In the conjugate plane \( l \) situated in the flame region the solid angle distribution over the beam cross section is evidently the same. The diameter of the central uniform area is as follows:

\[
2R_u = D_s - \frac{X h_s}{f_s}.
\]  \( \text{(A7)} \)

This equation is valid at \( 0 < X < X_o \). At \( X = X_o \) as illustrated in the figure A2, \( R_u = 0 \), and the eq. (A7) yields

\[
X_o = \frac{D_s f_s}{h_s}.
\]  \( \text{(A8)} \)
In the cross section $X = X_o$ (plane II) the solid angle at the axis has its maximum value compared to all other points of the flame region because in the conjugate point the situation is similar to that in the plane II of Fig. A1, where eq. (A4) is valid.

For $X > X_o$ and $r < R_u$ the radiation flux entering the slit is restricted by the lens flame, which acts as aperture stop, whereas $R_u$ obeys the eq.

$$2 \ R_u = X \ \frac{h_s}{f_s} - D_s \quad .\quad (A9)$$

The total diameter of the beam for all $X$ values is as follows

$$2 \ R_l = \frac{h_s X}{f_s} + D_s \quad .\quad (A10)$$

Consequently, the diameters of all the other stops of the arrangement (optical ports diameters $d_s$ and $d_l$ and the diameter of lamp condenser $D_l$) must be selected based on the conditions:

$$d_s \geq 2 R_l(X_s) = \frac{h_s}{f_s} + D_s$$

$$d_l \geq R_l(X_l) = \frac{h_l}{f_s} X_l + D_s \quad (A11)$$

$$D_l \geq R_l(H) = \frac{h_s}{f_s} H + D_s$$

where $X_s$, $X_l$, $H$ are respective distances from the lens $S$. 
Eqs. (A7) - (A10) yield the formulas for the vignetted portion of the "parallel" beam cross section:

\[ \frac{2}{1 + \frac{x}{x_o}}, \quad x \geq x_o \]

\[ \frac{R_t - R_u}{R_t} = \]

\[ \frac{2}{1 + \frac{x_o}{x}}, \quad x < x_o \]  

(A12)
A.1.4. Concluding remarks

Note, that the beam patterns formed in the flame region in the case of rectangular monochromator slit \(a_s << h_s\) will be similar to the pictures shown in the Fig. A1 and A2. The equations obtained above for vertical longitudinal cross sections of the axisimmetric beam will be also valid for rectangular slit if \(h_s\) designates the height of the slit. For horizontal cross sections of rectangular case \(h_s\) in all the formulas must be substituted with \(A_s\).

The Figs. A1 and A2 show, that the beam patterns are strongly dependent on arrangement dimensions and axial position of the slit image. Consequently, the inhomogenities and fluctuations which occur in the scale comparable with \(R_i\) and \(R_o\) may contribute into the measured signal in a very different ways.

The above analysis provides merely a framework for detailed computation of the effect. The simple formulas and pictures given above may be readily used for practical selection of the instrument and evaluation of the results obtained in the measurement. Below a numerical example is presented.
A.1.5. An example of calculation

Compare the beam patterns shown in Figs. A1 and A2 for the following instrument characteristics:

\[ h_s = 1 \text{ mm}, \ f_s = 200 \text{ mm}, \ D_s = 10 \text{ mm}. \]

In the crossed beam arrangement (Fig. A1) the slit image \( h_s' = 10 \text{ mm} \) is placed at a distance \( C_s = 2200 \text{ mm} \) from the lens. Using eq. (A7) it can be shown that at

\[ 1800 \text{ mm} \leq x \leq 2400 \text{ mm} \]

about 90 percent of the beam cross section is "homogeneous".

In the "parallel beam" case (Fig. A2) the picture is entirely different. Eq. (A9) yields \( x_o = 2000 \text{ mm} \), i.e. at this axial distance all the beam cross section totally inhomogeneous. The interval of the optical axis where the inhomogeneous portion of the beam cross section is substantial (\( R_j/R_i < 50\% \)) as obtained from eq. (A12) is

\[ 1.5 x_o > x > 0.3 x_o \]

i.e. for \( x_o = 2000 \text{ mm} \) one obtains:

\[ 3000 \text{ mm} > x > 600 \text{ mm}. \]
THE EXAMPLES OF CALCULATION OF LINE-REVERSAL

OPTICAL ARRANGEMENT

EXAMPLE
The line-reversal instrument for temperature measurement in a shock tube, in a visible part of spectrum. The facility (shock tube) dimensions:
\[ H = 224 \text{ mm}; \]
\[ l_1 = 10 \text{ mm}; \]
\[ l_2 = 10 \text{ mm}; \]
\[ d = 11 \text{ mm}. \]

The detector is the tip of the quartz fiber \( h = 0.2 \text{ mm} \) in diameter, numerical aperture of the fiber \( A_n = 0.17 \) [21], respectively \( \phi' = 9.8^\circ \).

On the first step compare the geometric factor of the facility with that of the detector. The geometric factor of the detector (32):

\[ G_f = 0.180 \text{ mm}^2 \]

The geometric factor of the detector (33):

\[ G_d = 0.003 \text{ mm}^2 . \]

As in this case \( G_d < G_f \) we refer to Problem A - the calculation of cross sectional dimensions for the arrangement at given geometric factor of the detector \( G_d \).
A.2.1. The calculation of the arrangement

Let the image of the fiber tip be positioned in the plane of the source-side window and the diameters of the ports are equal.

\[
d_l = \sqrt{\frac{4}{\pi} \sqrt{G_d} (l_s + H)} = \sqrt{\frac{4}{\pi} \sqrt{0.003} (10 + 224)} = 4.0 \text{ mm}
\]

\[
d_s = D_s = d_l = 4.0 \text{ mm}
\]

\[
D_l = d_l (1 + \frac{2 \cdot l_s}{l_s + H}) = 4.0 \left(1 + \frac{2 \cdot 10}{10 + 224}\right) = 4.3 \text{ mm}
\]

\[
S_s = h_s \sqrt{\frac{(l_s + H)}{\frac{4}{\pi} \sqrt{G_d}}} = 0.2 \sqrt{\frac{\pi}{4} \frac{(10 + 224)}{\sqrt{0.003}}} = 11.6 \text{ mm}
\]

The focal distance of the lens \( S \) is easily obtained for given distance from the object to the lens and distance from the image plane to the lens \((l_s + H)\).

\[
f_s = \frac{1}{\frac{1}{S_s} + \frac{1}{H + l_s}} = \left(\frac{1}{11.6} + \frac{1}{226 + 10}\right) = 11.0 \text{ mm}
\]

Illuminating part of the arrangement

Illuminating part (figure 1) comprises the calibrated source and the lens \( l \). The source \( l \) is characteri-

* the numbers refer to the eqs. in the main body of the text.
zed by irradiating surface area and the angle \( \phi \) within which the Lambert's law is valid. Let the irradiating surface have the diameter \( h_i \). This surface is optically conjugate to the surface of the detector, consequently the value of \( \phi \) and \( h_i \) should obey the equations:

\[
\tan \theta_1 \geq \frac{D_1}{2S_l}
\]

\[
h_i \geq h_s
\]

(A13)

where \( h_s'' \) is the entrance-slit image formed by the lenses \( S \) and \( L \).

\[
h_s'' = h_s \cdot \frac{S_l}{1_l} = h_s \cdot \frac{H + l_s}{1_l} \cdot \frac{S_l}{S_s}
\]

Accounting for the relation between \( h_s \) and \( h_s'' \) the eqs. (A.13) yield:

\[
\tan \theta_1 \geq \frac{D_1}{2S_l}
\]

(A14)

\[
h_i \geq h_s \cdot \frac{H + l_s}{1_l} \cdot \frac{S_l}{S_s}
\]

(A15)

Define
If the calibrated source is the lamp with the flat filament and the only requirement to be fulfilled is (A.15). In this case

\[ \tan \theta = \frac{D_1}{2 S_1} \]

The filament width usually is not larger than 2 mm.
Consequently, (A.16) yields

\[ S_1 \leq 5 \text{ mm} \]

This condition is difficult to realize. In order to increase \( S \), the input data for the example should be amended \( I \), value must be increased.
Let \( S_1 = 10 \text{ mm}, I = 40 \text{ mm} \). The corresponding focal distance for lens \( l \) is

\[ f_1 = 8 \text{ mm} \]

Consequently, the (A.15) yields

\[ h_1 \geq 0.2 \cdot \frac{224 + 10}{40} \cdot \frac{10}{11.6} = 1.0 \text{ mm} \]

The amendment of \( I \), will cause only the change of \( D \), which in accordance with (47) will increase up to 5.4 mm.
If the calibrated source is a black body model or the fiber tip illuminated by the radiation source, both
conditions (A.14) and (A.15) should be fulfilled. The maximum angle for black-body model radiation depends on its design and usually does not exceed 10°. For the quartz fiber this angle is 9.8°. In the example to be considered the reference source is the quartz fiber. Compare (A.14) with calculated above parameters of illuminating portion of the arrangement:

\[ \frac{D_l}{2 S_l} = 0.27 ; \quad 15° > 9.8° . \]

The value of \( S_l \) should therefore increase up to at least 17 mm.

In this case we obtain:

\[ f_e = 12 \text{ mm} \]
\[ h_e \geq 1.7 \text{ mm (see (A3))} , \]
\[ \theta_l = 9° . \]

To conclude sect. A2.1 note that in this example \( G_f \gg G_d \), therefore any combination of \( d_1 \) and \( d_s \) in figure 4b within the limits \( d_1 \leq 10 \text{ mm} \) and \( d_s \leq 10 \text{ mm} \) is suitable. (In all this cases \( G_d = \text{const} \) and \( d_1 \) is related to \( d^3 \) by the equation (38)).

Moreover, as \( G_f \gg G_d \), the crossed-beam - and parallel beam arrangements can be also used for the measurements. The optimized parameters for such arrangements as defined in sect. 3 are given below.
A.2.2. The crossed-beam arrangement
(see sect. 3.1.)

The equation (19) yields:

\[
d_l = 4 \sqrt{G \cdot \frac{256}{\pi^2} \cdot \frac{(H + \frac{1}{2})^2}{(1 + \frac{2}{H})^2}} = 7.7 \text{ mm}.
\]

Eq. (18):

\[
ds = 0.5 \cdot d_l \cdot \frac{1 + \frac{2}{H}}{1 + \frac{1}{H}} = 4.0 \text{ mm}.
\]

Eq. (24):

\[
h_s = 0.5 \cdot ds = 2.0 \text{ mm}.
\]

Eq. (20):

\[
D_s = 0.5 \cdot d_l \cdot (1 + \frac{2}{H}) = 4.2 \text{ mm}.
\]

Eq. (23):
\[ D_f = d_f + d_f \left( \frac{l_e}{H} \right) \left( 1 + \frac{1}{2 \left( 1 + \frac{l_s}{H} \right)} \right) = 7.9 \text{ mm} \]

\[ S_s = \frac{2 h_s (l_s + H)}{d_f} = 12.2 \text{ mm} \]

(The selection of illuminating part of the arrangement is similar to sect. A.2.1.).
A.2.3. The parallel-beam arrangement
(see sect. 3.2.)

The equation (28) yields:

\[ d_l = \sqrt{\frac{G}{\pi}} \left( \frac{16}{H} (1 + \frac{l_s}{H}) \right) = 8.1 \text{ mm} \]

Eq. (27):

\[ d_s = 0.5 \frac{d_l}{1 + \frac{2 l_s}{H}} = 4.2 \text{ mm} \]

Eq. (29):

\[ D_s = \frac{d_l}{2} = 4.0 \text{ mm} \]

Eq. (31):

\[ D_l = 8.3 \text{ mm} \]

Eq. (30):

\[ f_s = \frac{2(l_s + H)}{d_l} \cdot h_s = 11.5 \text{ mm} \]
EXAMPLE 2.

Line-reversal instrument for temperature measurement in the combustor with gas flow diameter 1150 mm, the thickness of alumina-brick refractory walls being 580 mm. The measurements are conducted in infrared spectral range.

The facility dimensions:

- \( H = 2600 \text{ mm} \),
- \( l_s = 300 \text{ mm} \),
- \( l_t = 200 \text{ mm} \),
- \( d = 19 \text{ mm} \).

(Maximum allowable diameters of optical ports are restricted by facility design and performance conditions).

The spectral detector is grating monochromator with photoelectric output signal. The entrance slit is a circle 1 mm in diameter, the colligating mirror has the diameter \( D_c = 17 \text{ mm} \) and focal distance \( f_c = 126 \text{ mm} \). Consequently

\[
\tan \theta = \frac{D_c}{2 f_c} = 6.7 \times 10^{-2}, \theta = 3.8^\circ.
\]

"Optimum" geometric factor for the facility (48):

\[
G_{f,\text{opt}} = 0.0096 \text{ mm}^2.
\]

Geometric factor of the detector (33):

\[
G_d = 0.0111 \text{ mm}^2.
\]

Since in this example \( G_d < G_f \), it is of interest to consider the "Problem B", i.e. to find the optical arrangement parameters providing maximum of \( G \) at optical ports diameter.
\[ d_I \leq d, \ d_s \leq d \]

Consider the line-reversal optical arrangement with the entrance slit image placed into the plane of source-side window (sect. 4). The eq. (45) yields:

\[ d_I = \sqrt{\frac{4}{\pi} \sqrt{G_d} \left( l_s + H \right)} = \sqrt{\frac{4}{\pi} \sqrt{0.0096} \left( 300 + 2600 \right)} = 19 \text{ mm} , \]
\[ d_s = D_s = d_I = 19 \text{ mm} . \]

Eq. (47):

\[ D_I = d_I \left( 1 + \frac{2 \ l_I}{l_s + H} \right) = 19 \left( 1 + \frac{2 \cdot 0.200}{300 + 2600} \right) = 21.6 \text{ mm} \]

Eq. (46):

\[ S_s = h_s \sqrt{\frac{l_s + H}{\frac{4}{\pi} \sqrt{G_d}}} = 1 \sqrt{\frac{300 + 2600}{\frac{4}{\pi} \sqrt{0.0096}}} = 152 \text{ mm} . \]

(The selection of illuminating part of the arrangement is similar to sect. A.2.1.).
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FIGURE CAPTIONS

Figure 1. The optical line-reversal arrangement considered in Section 3.

Figure 2. The "crossed beam" optical line reversal arrangement (the nomenclature is shown in Fig. 1).

Figure 3. The "parallel beam" optical line-reversal arrangement (the nomenclature is shown in Fig. 1).

Figure 4. The lamp-side window diameter $d_l$, as a function of detector-side window diameter $d_r$ at constant etendue $G$.

Figure A1. The "crossed beam arrangement". A axisymmetric optical beam pattern formed in a flame region by the monochromator slit and the frame of lens S (a) and the distributions of a solid angle in typical cross sectional planes (b).

Figure A2. The "parallel beam" arrangement. An axisymmetric optical beam pattern formed in a flame region by the monochromator slit and the frame of lens S (a) and the distributions of a solid angle in typical cross sectional planes (b).
Figure 1. The optical line-reversal arrangement considered in Section 3.
Figure 2. The "crossed beam" optical line-reversal arrangement (the nomenclature is shown in fig.1)

Figure 3. The "parallel beam" optical line-reversal arrangement (the nomenclature is shown in fig.1)
FIGURE 4. The lamp-side window diameter \( d_1 \) as a function of detector-side window diameter \( d_s \) at constant etendue \( G \).
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