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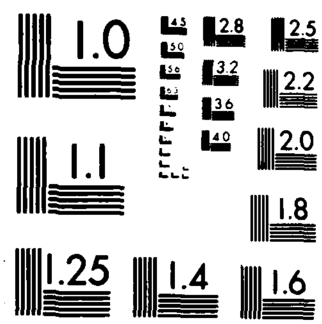

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Research Report

NONCONTACT PHOTO-THERMAL PROBE-BEAM DEFLECTION MEASUREMENT OF THERMAL DIFFUSIVITY IN AN UNCONFINED HOT GAS

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A pulsed CO_2 laser beam is used to produce a transient thermal refractive-index-gradient in nitrogen gas doped with trace amounts of absorbing Freon 12 at temperatures from 25°C to 425°C. The diffusion of this gradient is probed by a continuous HeNe laser beam parallel but displaced from the pulsed beam. The observed deflection signal agrees well with the theory of Jacson et al. (1981), and signal.

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By

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NONCONTACT PHOTO-THERMAL PROBE-BEAM DEFLECTION MEASUREMENT OF THERMAL DIFFUSIVITY IN AN UNCONFINED HOT GAS

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ABSTRACT: A pulsed CO_2 laser beam is used to produce a transient thermal refractive-index-gradient in nitrogen gas doped with trace amounts of absorbing Freon 12 at temperatures from 25°C to 425°C. The diffusion of this gradient is probed by a continuous HeNe laser beam parallel but displaced from the pulsed beam. The observed deflection signal agrees well with the theory of Jackson *et al.* (1981), and thermal diffusivity or gas temperature can be derived from the signal.

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*On leave from Institut d' Optique Théorique et Appliquee, Centre Universitaire d' Orsay, B. P. No. 43, 91406 Orsay Cedex, France.

The Photo-Thermal Probe-beam Deflection (PTPD) method developed by Boccara and co-workers[1-5] has gained much attention recently as a noncontact spectroscopic measurement tool in gases as well as in condensed matter. PTPD relies on the generation of a thermal Refractive-Index-Gradient (RIG) in or near a sample due to the absorption of a "pump" beam, and the detection of this RIG by a continuous probe beam. In most PTPD work,[1-8] the pump beam is a continuous modulated laser beam obtained by chopping at tens of Hz, and the probe beam deflection is modulated correspondingly. However, Rose *et al.*[9] have recently used a pulsed laser for PTPD spectroscopy in a flame. The advantages of using pulsed laser are that much higher power is available and also measurements related to a transient thermal RIG can be made.

We have made a first experimental investigation of the evolution of the transient thermal RIG produced by a pump laser pulse and detected by a spatially separated probe beam. Unlike the previous PTPD investigations which are mainly spectroscopic, we show here that thermal diffusivity D or gas temperature can be obtained by analyzing the time-dependent PTPD signal shape. This provides a new method for noncontact monitoring of temperature or material composition that affect D. The present experiment is designed to measure the thermal RIG in an unconfined hot gas to mimic an open flame. It should be noted that a pulsed laser can also generate an acoustic RIG in a flame observable with probe-beam deflection.[10]

Our experimental apparatus is indicated in Fig. 1. The gas cell is made from a block of aluminum alloy of dimension about 5 cm$\times$4 cm$\times$1.8 cm. Suitable cavities are made in the aluminum block to allow cartridge heaters to be inserted for heating of the gas. Two open windows of dimension 2 mm$\times$5 mm allow the entrance and exit of the laser beams. A slow stream of nitrogen with 0.11% Freon 12 (pre-mixed gas from

Matheson) flows into the aluminum cell. The purpose of the low concentration of Freon is to provide some weak absorption of the pump beam, which is a CO_2 laser beam at 10.834 μm, with pulse width 150 μsec and peak power 50 Watt at 30 Hz repetition rate. The gas flow rate is smaller than 10^{-2} cc/sec to ensure that the gas temperature in the measurement chamber is at the cell temperature. Both CO_2 laser beam and the probe HeNe laser beam are focused at the center of the cell by a ZnSe lens of 125 mm focal length and a glass lens of 250 mm focal length, respectively. The two laser beams are parallel and in the same horizontal plane. They are separated by a displacement r that is adjustable by an accurate translation platform carrying the HeNe laser and its focusing lens and the photodetector. The cell, the CO_2 laser beam with the ZnSe focusing lens and the KRS-5 beam splitter are fixed in position. The horizontal geometry of the two laser beams is used to minimize any effects due to flow or convection, as indicated in Sell's work.[8] The HeNe laser beam emerging from the cell is transmitted through a quartz plate (which blocks the CO_2 laser beam); after some suitable propagation distance, the defocused HeNe laser beam is incident on a small aperture which is positioned asymmetrically with respect to the probe beam cross section. This aperture is used[11,12] to convert a probe deflection into an intensity variation, which is monitored by a photodiode-amplifer assembly (UDT model 600). The photodiode signal S(r,t) is digitized by a Tektronix 7854 oscilloscope, which accumulates the signal and transmits it to a personal computer (IBM PC) via an IEEE 488 bus. The IBM PC stores the signal, prints it on a matrix printer, as well as generates theoretical signals to compare with the experimental ones.

The theoretical PTPD signal shape S(r,t) can be derived according to the work of Jackson *et al.*[4] In their Eq. (28), they show that a pulsed laser beam of Gaussian radius a, energy E_0 and pulse duration t_0 produces a temperature gradient $\partial T/\partial r$ in an infinite medium with weak absorption coefficient α given by

$$\frac{\partial T}{\partial r} = \frac{-\alpha E_0}{2\pi k t_0 r} = \left[\exp\left(\frac{-2r^2}{a^2 + 8Dt}\right) - \exp\left(\frac{-2r^2}{a^2 + 8D(t-t_0)}\right)\right] \tag{1}$$

for $t>t_0$. Here t is the time measured from the starting of the laser pulse and k is the thermal conductivity of the medium. The corresponding[11] probe defection angle $\phi(r,t)$ is

$$\phi(r,t) \approx \frac{\ell}{n_0} \frac{\partial n}{\partial T} \frac{\partial T(r,t)}{\partial r} \tag{2}$$

where ℓ the interaction path length ($\approx$1.8 cm in our experiment), n_0 is the ambient refractive index of the gas and $\partial n/\partial T$ is the temperature coefficient of the refractive index. The observed signal at the photodiode is (for small deflection angles)

$$S(r,t) = GI_p'(r_1)L\phi(r,t) \tag{3}$$

where G is a constant depending on the photodiode sensitivity and gain, $I_p'(r_1)$ is the lateral spatial derivative of the probe beam intensity distribution at the aperture position r_1 and L is the "lever arm" of the probe beam (*i.e.*, distance from the cell center to the aperture and is about 22 cm in our experiment). Combining Eqs. (1)-(3), we have

$$S(r,t) = K\,\frac{\alpha E_0}{r}\left[\exp\left(\frac{-2r^2}{a^2 + 8Dt}\right) - \exp\left(\frac{-2r^2}{a^2 + 8D(t-t_0)}\right)\right] \tag{4}$$

where

$$K = -\frac{1}{2\pi k t_0}\,\frac{\ell}{n_0}\,\frac{\partial n}{\partial T}\,GI_p'(r_1)L \tag{5}$$

is independent of t and r. Equation (4) is valid for $t>t_0$, and is the basis of pulsed PTPD measurement. It shows that α can be measured as a function of excitation wavelength, as done in previous PTPD measurements.[1-9] It also shows that D can be measured by fitting the observed signal shape S(r,t) to the form in the square bracket in Eq. (4), as done in the present work.

Our signal observed on the oscilloscope for x=0.126 cm and cell temperature T_c=25°C is shown in Fig. 2. Here, we see that the photodiode signal has a fast component and a slow component. The fast component is not appreciably delayed from the laser pulse on the scope time scale of 1 ms/div; this component is due to the acoustic RIG probe-beam deflection effect,[10-12] which occurs at a time delay of about 4.2 μsec from the laser pulse for a sound speed of 3×10^4 cm/sec. The signal variation after the initial sharp spike is due to the thermal RIG and follows the shape indicated in Eq. (4).

The signals averaged for 100 laser shots stored in the computer for two cell temperatures T_c are shown in Fig. 3. The signal magnitude is observed to decrease as temperature increases, in accordance with Eq. (2), since $\partial n/\partial T$ goes as T^{-2} for an ideal gas. We clearly see that the signal peak moves to earlier times as temperature increases, indicating that thermal diffusivity D increases with temperature. By fitting Eq. (4) to the observed signals, we can obtain the theoretical signals shown in Fig. 3 with the values of D_{fit} as indicated. These theoretical curves are calculated with the following parameters: laser pulse width=150 μsec, excitation beam Gaussian radius=0.07 cm, and separation between excitation and probe beam=0.105 cm. In reality, the excitation beam is not Gaussian but has annular structures, so that the theoretical fits are not perfect.

Table 1 indicates some of our experimental results for a range of cell temperature T_c. The fitted diffusivity values D_{fit} increases very substantially with temperature. The dependence of thermal diffusivity on temperature for N_2 at 1 atmosphere has been extensively measured in the literature,[13-17] generally with the use of wires or probes inserted into the gas. Using the diffusivity data listed by Rutherford *et al.*[13] (which is consistant with data from other workers), we can convert the measured D_{fit} in Table 1 into corresponding averaged gas temperature $\overline{T}_g$. We see that $\overline{T}_g$ is generally somewhat cooler than the cell body temperature T_c. This is probably due to cooling effects occurring at the windows.

In conclusion, we have demonstrated a noncontact pulsed PTPD measurement in an unconfined hot gas for monitoring thermal diffusivity or the related temperature. The observed signal shape $S(r,t)$ agrees well with the theoretical form of Jackson *et al.*[4] Such a nonintrusive method should be valuable for measurements *in situ* in open medium like flames or in other hostile environments.

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Table 1

Cell Temperature, Fitted Thermal Diffusivity From the Signal and the Corresponding Average Gas Temperature Based on Literature (Ref. 13)

$\bar{T}_c$(°C)	D_{fit} (cm^2/sec)	$\bar{T}_g$(°C)
25	0.21	25
48	0.230	42
79	0.258	64
131	0.32	110
155	0.369	141
222	0.47	205
233	0.498	221
312	0.574	267
423	0.810	386

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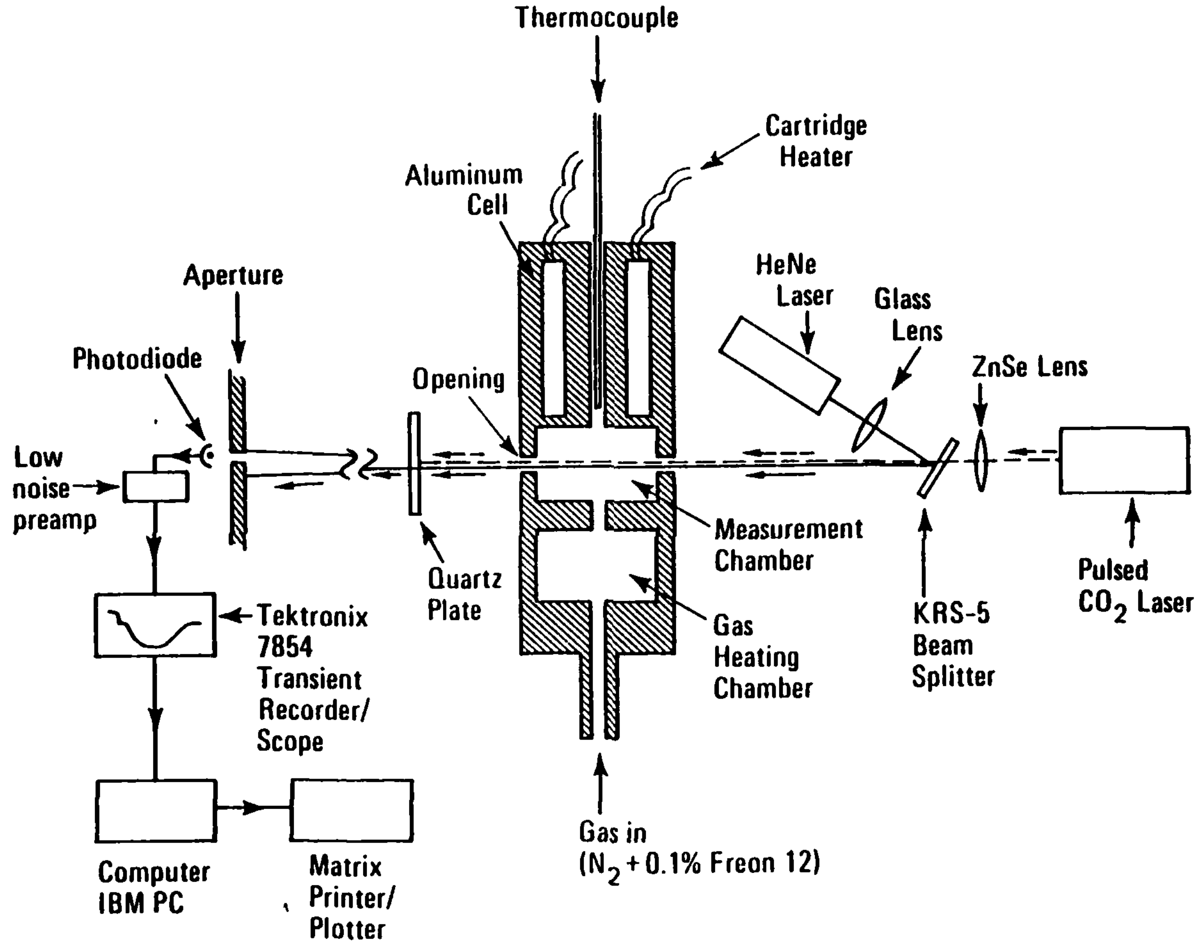

Figure 1. Experimental arrangement.

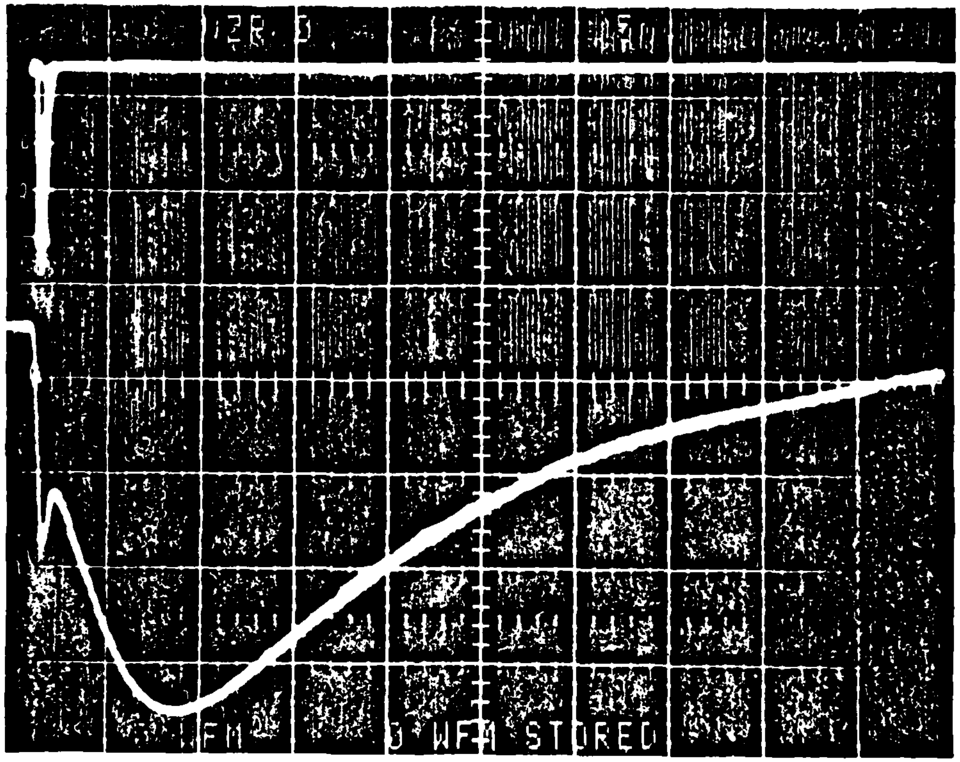

Figure 2. The upper oscilloscope trace shows the CO_2 laser pulse shape, and the lower trace shows the observed photothermal deflection signal for N_2 at 25°C for beam separation $r=0.105$ cm. Horizontal scale is 2 ms/div.

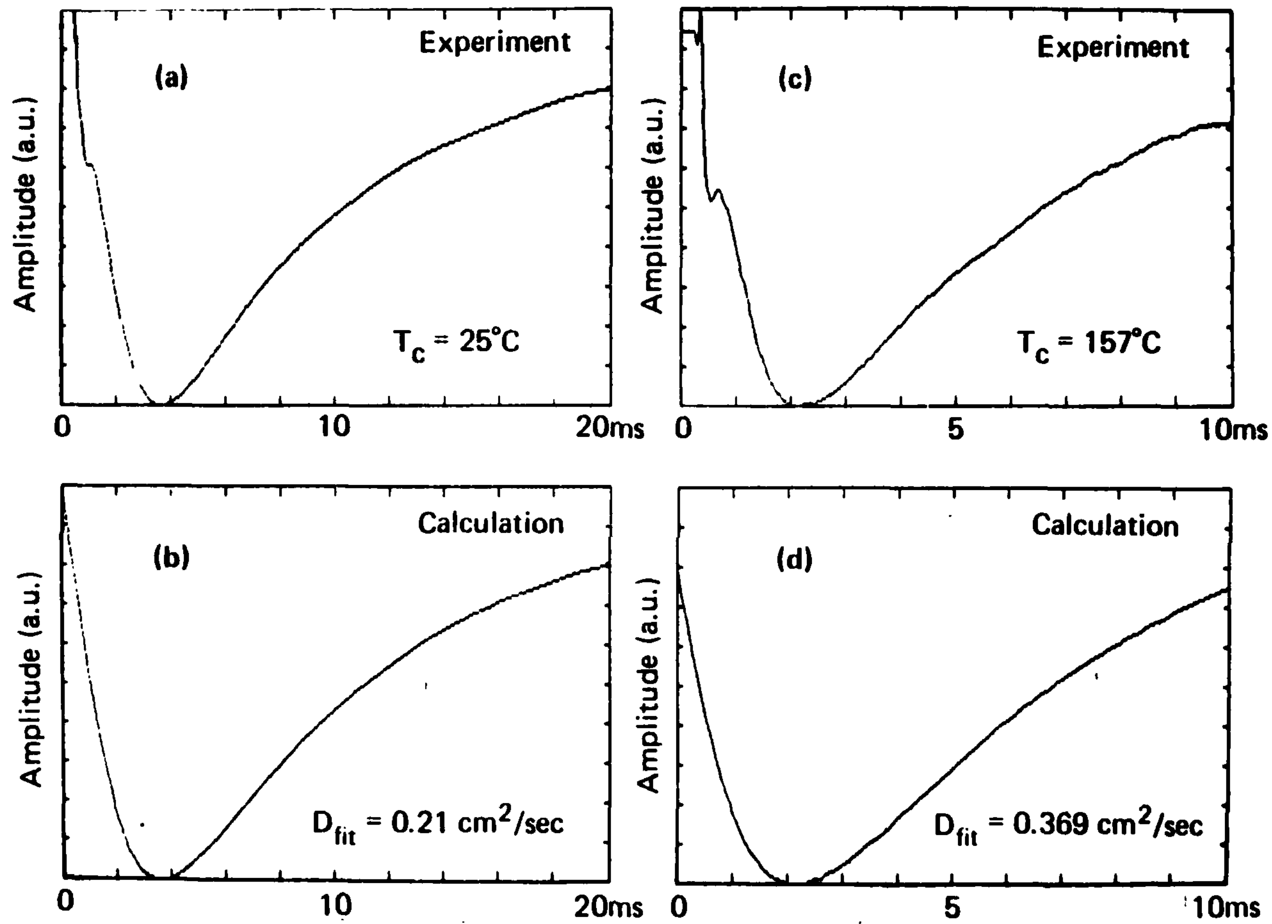

Figure 3. Observed photothermal deflection signal at two different temperatures. (a) T_c=25°, (c) T_c=157°c for beam separation r=0.105 cm, as compared to the theoretical deflection signals using the fitted values of thermal diffusivity (b) D_{fit}=0.21 cm^2/sec, (d) D_{fit}=0.369 cm^2/sec.

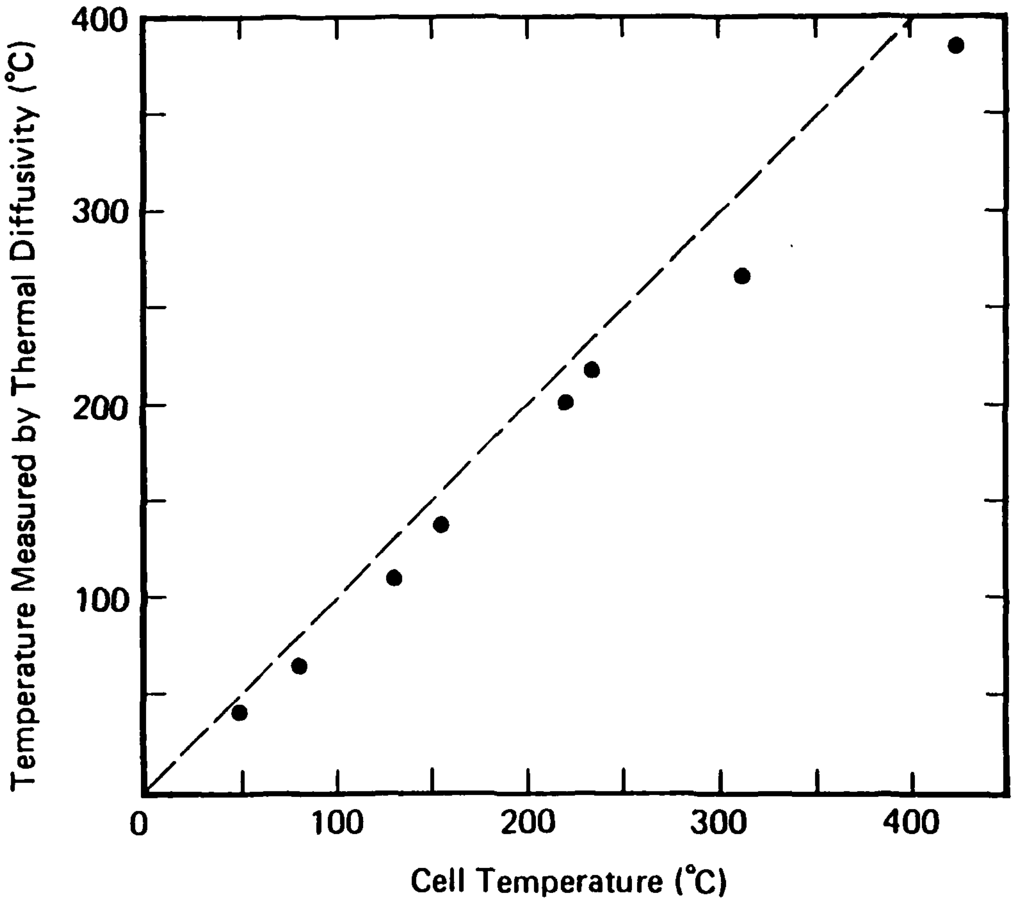

Figure 4. Measure "mean" gas temperature ($\overline{T}_g$) based on the values of D_{fit} as a function of cell temperature T_c given by a thermocouple. The dotted line indicates the case when the gas column being monitored is of uniform temperature at T_c.