A LASER TOMOGRAPHIC INVESTIGATION OF LIQUID FUEL SPRAYS

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(NASA-CR-162765) A LASER TOMOGRAPHIC INVESTIGATION OF LIQUID FUEL SPRAYS (Sheffield Univ.) 25 p HC A02/MF A01 **N80-17399**

CSCL 20D **Unclas**

G3/34 47170

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Subject Matter:

(3) Experimental Methods (Particle Sizing)

(7) Heterogeneous Combustion (Vaporization of Liquid Fuel)

EIGHTEENTH SYMPOSIUM (INTERNATIONAL) ON COMBUSTION

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Abstract

A light scattering technique is combined with a tomographic transformation to convert line of sight integrated data, measured in sprays, to measurements of droplet size and concentration in volume elements within the spray. The technique is developed and assessed by systematic experiments in axisymmetric sprays generated by twin-fluid atomisers. The angular distribution of forward scattered light from a laser beam passing through the spray is measured for a series of scans with the beam passing through different sections of the spray at the same axial position. This data is transformed numerically into 'point' measurements of droplet size distribution and volume concentration and these measurements are compared with data obtained by analysis of spark photographs obtained in the same spray. The good agreement found shows that, provided certain conditions are satisfied by the local spray structure, the new technique provides information on spray structure, similar in detail and extent to that derived by photography, but with reduced experimental time. The technique is applied to an investigation of a kerosene spray vaporizing in a hot gas stream. Measurements are made of local droplet size distributions and vaporization rates in the spray. Tomographic data analysis increases the useful information which can be derived from light scattering measurements in sprays and the method provides useful data on the detailed physical structures of twin-fluid atomised sprays.

1. Introduction

The investigation, prediction and modelling of the vaporization and combustion of fuel sprays, require detailed information on the local spray structure, as specified by spatial distributions of volume concentrations, droplet size distributions and volume fluxes. For certain cases more detailed information, such as droplet size/velocity correlations, are of importance. There is a need for diagnostic tools for obtaining this information, accurately and rapidly. Imaging techniques, such as spark photography[1] and holography, have been developed to provide measurements of droplet size distributions and concentrations with optimum experimental accuracy. However, even when using automated image analysis systems, the imaging techniques tend to be very slow and inconvenient when detailed measurements of spray structure, involving many measurement positions, are required. Thus there has recently been considerable development work on the application of light scattering techniques to investigate spray structure. When photodetectors are interfaced with computers, light scattering techniques have the potential for very rapid measurement of particle size. Light scattering techniques can be divided into two types: Single Particle Counting techniques, where individual particles are measured as they pass through a measurement volume, and Particle Cloud techniques, where the scattered light from many particles in a light beam is analysed to provide an overall size distribution. The two techniques are compatible: the Single Particle Counting technique[2] provides very detailed, time dependent information on local spray structure, including size and velocity data, while the Particle Cloud[3] technique has only been used to produce a very rapid measurement of overall size distribution for an integrated path across the spray. During our previous investigations of fuel sprays, it became apparent that the Particle Cloud technique has the potential for providing more detailed information on spray structure. In addition, overall size distributions can be very misleading when the distributions of droplet sizes and numbers across a spray are inhomogeneous, as is often found to be the case.

This paper describes the development and application of a Malvern Instruments ST 1800 Particle Size Meter and its software to provide information on local size distributions and volume concentrations in sprays, with good spatial resolution, rather than an overall spray size distribution. The technique is applied to an investigation of fuel sprays vaporizing in a hot gas flow.

The spray structure and the interrelationship between structure and the measurements produced by the light scattering and photographic techniques have been investigated and potential sources of error and discrepancy between different techniques are discussed.

2. Size Distribution Measurement by Light Scattering

In the standard Malvern instrument, a parallel 9 mm diameter HeNe laser beam is passed through the spray and the forward scattered light is collected by a Fourier transform lens arrangement. By using this arrangement, particles with the same diameter and the same uniform illuminating light intensity, produce the same radial, scattered light intensity distribution at the focal plane of the lens. The scattered light energy contributions from all droplets in the beam are summed directly so that the light power distribution at the focal plane is unambiguously related to the size distribution of particles illuminated by the laser beam. As described by Swithenbank et al,[3] a photodetector, which consists of 30 concentric annulli, is used to measure the angular distribution of scattered light power, from which the particle size distribution is calculated by using Fraunhofer diffraction theory.

In practice the illuminating intensity is not the same for all droplets, because of the non-uniformity of the radial light distribution across the laser beam. However this does not affect the shape of the measured size distribution provided that the spray is homogeneous across the beam. In addition, in spite of this non-uniformity, it is possible to calculate the volume or number density of particles in the beam when a calibration coefficient is established for the system (by comparison with photographic results or by measurements in a known, well defined particle laden flow).

Thus, in its standard form, this particle sizing instrument is designed to derive rapidly an 'overall' size distribution for a complete width of a spray. Difficulties arise when a more detailed knowledge of the spatial distribution of droplets in the spray is required, or when the spray is highly structured. The 'line-integral' nature of the particle size distribution, does not directly provide information on how droplets are distributed across the spray. In highly structured sprays such information is of practical importance. For example, many atomisers produce sprays which have narrow regions containing relatively large droplets or relatively high volume concentrations of droplets. The detection of these regions is essential and furthermore, the line-integrated size distribution, derived from the particles in the beam, will differ according to whether the beam passes through this region or not. In addition the size distribution of droplets in a relatively narrow beam, passing through the centre of the spray, will not correspond exactly to the size distribution for all droplets passing through the plane containing the beam, and perpendicular to the spray axis. This is particularly true for sprays which are radially non-homogeneous. For example, for an axisymmetric spray, the size distribution measured by passing a beam through the spray centre, is weighted towards droplets near the centre of the spray because, effectively, a line integral is used to approximate a distribution which should be obtained by integrating over a complete cross-section. It is also noted that there is a separate problem created by droplets moving with different velocities in different regions of the spray, and in certain cases, large droplets may have significantly different velocities than small droplets. However we restrict ourselves here to the consideration of spatially averaged size distributions, whilst recognising that temporally averaged distributions are also of interest, but require separate or simultaneous measurement of droplet velocities.

3. Tomographic Transformation of Scattered Light Data for Sprays

With the authors' requirements for making detailed spatial mappings of droplet size distributions and concentrations in vaporizing sprays, it was considered worthwhile to investigate the further development of the Malvern Instrument to overcome some of the restrictions noted above, while retaining the instrument's advantages of experimental speed and convenience. The problem under consideration here, is the transformation of scattered light data measured, effectively, for line integrals along the laser beam traversing different parts of the spray, into two dimensional distributions of particle sizes and concentrations in a plane across the spray. This data transformation is known generally as 'tomography' (tomos Gk - a slice) and it has been used for several types of system in recent years; particularly for the cases of medical X-ray brain and body scanners. With the latter applications in mind, Cormack[4, 5] derived general formulae by which a two dimensional distribution of a function (the gamma ray absorption coefficient) is represented by its line integrals, which are measured by the scanner. The data inversion required for transforming these integrals into the required distribution, is achieved either by direct numerical solution or by Fourier transform procedures.

Figure 1 shows how this approach is applied for the present case of a laser beam traversing a spray. The cross-section of the spray is shown to be circular, but in general this is not a necessary condition. The total power P of the unscattered laser beam decreases as the beam traverses the spray in a manner determined by the distribution of extinction coefficient k along the beam. We divide the problem into two interconnected components: derivation of the k distribution in the r, θ plane across the spray and derivation of distributions of particle sizes and volume concentrations in this plane. It is assumed that the spray structure is statistically stationary so that all quantities used here are time averaged and the effects of fluctuations with time are not considered.

As shown in Figure 1, scan 'L' corresponds to a measured power P_L for the attenuated beam leaving the spray (causing the delta function at the centre of the detector) and a scattered light intensity distribution $I_{S_L}(\omega)$ is measured in the form of the light power collected at a series of annular detectors. This scattered light power can be represented by $\bar{P}_{S_L}(\omega)$; the scattered light power falling on a disc with radius a, where $\omega = a/f$

It is assumed that the width of the laser beam is very much less than the width of the spray, and also less than the scale of any inhomogeneity of internal spray structure. For convenience the complete spray is assumed to be contained by the circle r = 1. The beam attenuation is related to the line integral of k along the beam, for scan L, by:

$$P_L = P_o \exp\left[- \int_L k(s)ds \right] \qquad (1)$$

where P_o is the laser power on entry to the spray.
The incident light power at a point distance s along the beam is

$$P_{(r,\ \theta)} = P_o \exp\left[- \int_o^{(1-p^2)^{\frac{1}{2}} + r \sin(\phi-\theta)} k(s)ds \right] \qquad (2)$$

One can define $P'(p, \phi) = \ln (P_o/P_L) = \int_L k(s)ds$ where P' can be measured from scan L. The general problem is thus to convert measurements of $P'(p, \phi)$, obtained with variation in both p and ϕ, into the distribution $k(r, \theta)$. The domains of both P' and k are unit circles and, for the analogous radiological absorption problem, Cormack[4] showed that by expanding these quantities in their Fourier series:

$$k(r, \theta) = \sum_{n=-\infty}^{\infty} k_n(r) \exp(in\theta) \quad \text{and} \quad P'(p, \phi) = \sum_{n=-\infty}^{\infty} P'_n(p) \exp(in\phi),$$

then the Fourier coefficients k_n of the required variable can be derived from the coefficients for the measured variable by the solution:

$$k_n(r) = -\frac{1}{\pi}\frac{d}{dr}\int_r^1 \frac{P_n'(p)\cos(n\cos^{-1}(p/r))\,pdp}{(p^2 - r^2)^{\frac{1}{2}}\,p} \qquad (3)$$

The particle size distribution, at any point in the spray cross-section, must be derived from the angular distributions of scattered light power $\overline{P}_s(\omega)$, measured for scans with variation in both p and ϕ. Because of the Fourier transform lens system, the scattered light power collected within a circle radius a at the detector, is the linear summation of all the light scattered within the angle, $\omega = a/f$, for the full length of the beam in the spray. In the general case the light power of the beam is attenuated as it passes through the spray in accordance with Equation 2. Thus the size distribution derived from the overall scattered light $\overline{P}_s(\omega)$ is not necessarily a linear summation of all the droplets within the laser beam but, rather, there is a bias towards that part of the spray nearest to the laser, where the illumination is greatest.

At this point two assumptions are made: firstly the light scattering from the particles at a distance s along the beam, is assumed to correspond to that produced by an illuminating power P at that position; secondly the effects of multiple scattering are assumed to be insignificant. For scan L the scattered light within angle ω, from an elemental unit length of the spray in the laser beam, is $P_s(s, \omega)$. This is related to the local absolute volume distribution of droplets V(D) by an equation of the form

$$P_s(s, \omega) = c\,P(s)\int_{D_{min}}^{D_{max}} \frac{V}{D}\,\chi\,(D, \omega)\,d(D) \qquad (4)$$

where D is droplet diameter, c is a constant which depends on the distribution of light across the laser beam and χ is the scattering function, which can either be derived from geometrical optics[5] or the full Mie theory. The total collected light in angle ω, for one scan, with coordinates (p, ϕ) is given by

$$\bar{P}_s(\omega, p, \phi) = \int_L P_s(s, \omega)\, ds \qquad (5)$$

One can again write the known and unknown distributions, $\bar{P}_s(\omega, p, \phi)$ and $P_s(\omega, r, \theta)$ respectively, as Fourier expansions:

$$\bar{P}_s(\omega, p, \phi) = \sum_{n=-\infty}^{\infty} \bar{P}_{s_n}(\omega, p) \exp(in\phi) \quad \text{and} \quad P_s(\omega, r, \theta) = \sum_{n=-\infty}^{\infty} P_{s_n}(\omega, r) \exp(in\theta)$$

and the known and unknown Fourier coefficients are related by the equation,

$$P_{s_n}(\omega, r) = -\frac{1}{\pi}\frac{d}{dr}\int_r^1 \frac{\bar{P}_{s_n}(\omega, p) \cos(n \cos^{-1}(p/r))\, pdp}{(p^2 - r^2)^{\frac{1}{2}}\, p} \qquad (6)$$

For the general case of a spray which may have no symmetry in its cross-section, and across which a significant proportion of the incident laser light power may be scattered and absorbed, the routine required to derive droplet size distributions at points within the spray would consist of:

(i) Measurement of the light extinction and angular light scattering, from $P^+(p, \phi)$ and $\bar{P}_s(\omega, p, \phi)$, for a series of scans of the laser beam with systematic variation of p and ϕ so that each point in the spray is intersected by sufficient scans to obtain the required spatial resolution.

(ii) Transformation of this data, obtained in the (p, ϕ) domain, into distributions within the spray, in the (r, θ) domain, of the local angular light scattering $P_s(\omega, r, \theta)$ and extinction coefficient $k(r, \theta)$. This can be achieved by Fourier transforming the measurements and solving equations (3) and (6). Obviously, in practice an exact solution cannot be obtained as a finite number of terms in the Fourier expansions are used, depending on the number of scans measured across the spray. An alternative transformation routine, utilised in certain radiological devices, would be to obtain directly a finite difference solution of equations 1 and 5 , by splitting the spray cross-section into many small elements and solving a set of simultaneous equations.

(iii) The local illuminating power $P(r, \theta)$ is derived from Equation 2 and Equation 4 is solved to obtain the local particle volume size distribution V(D). Because V(D) is in terms of absolute volume, the local volume concentration of particles in the spray can be derived, provided that the constant c, for the system, has been established.

As a first step, to establish the feasibility of this transformation of the light scattering data, investigations have concentrated on sprays which are closely axisymmetric. The existence of symmetry simplifies the data analysis procedure. Furthermore the sprays have been selected so that the extinction of light is not significant so that $P_L \simeq P_o$ for all scans. For these conditions all but the first Fourier expansion terms are zero and Equation 10 becomes

$$P_s(\omega, r) = -\frac{d}{dr}\left[\frac{r}{\pi}\int_r^1 \frac{\bar{P}_s(\omega, p)\, dp}{(p^2 - r^2)^{\frac{1}{2}}\, p}\right] \qquad (7)$$

This is analogous to the Abel transformation of spectroscopic data[6] used for measurements in axisymmetric gas flames.

4. Experiment and Results

Measurements have been made in sprays produced by twin-fluid atomisers in which both the liquid and atomising gas are introduced symmetrically so that the sprays should be axisymmetric. In the first set of experiments a Spraying Systems type II atomiser was used with air as the atomising fluid. This produces sprays which are nominally of the full cone type. The bulk of data have been derived for the spray ejecting vertically downwards into the ambient atmosphere and at an axial plane 150 mm from the atomiser. At this distance the total spray width was approximately 80 mm. The liquid flow rate was 1.43 x 10^3 mm^3/s and the air flow rate was 6.8 x 10^4 mm^3/s. The measurements consisted, in the first place, of an extensive series of spark photographs which were taken using a 1.5 m long MPP technical camera with 90 mm focal length lens, and 5 x 4 Polaroid Type 54 film. The magnification was 16x and droplets larger than approximately 5 μm could be detected. A 20 kV spark source, developed at Sheffield, was used. The photographs were analysed by a Cambridge Instruments Quantimet Image Analysis Computer using a technique developed by Yule.[1] This technique uses a prior calibration of the photographic and Quantimet systems obtained by photographing known particles with systematic variation of distance from the camera. By using this calibration the light distributions across images of droplets in spray photographs are analysed to derive the true droplet diameter and the position of the droplet in the camera depth of field. This permits the operator to define a depth of field within which droplets are to be measured. This was fixed at 7.5 mm for the present measurements giving a measurement control volume 7.5 mm x 8.7 mm x 11.4 mm.

Photographs were taken at intervals of 9 mm across the spray with the spray traversed in the direction along the axis of the camera. Sufficient photographs were taken to permit measurement of at least 2000 droplets at each position. The data were analysed to give droplet size distributions, volume median diameters $D_{vo.5}$ and droplet volume concentrations at each position. The volume median diameters across the spray are plotted in Figure 2. The spray was found to be closely axisymmetric with $D_{vo.5}$ increasing from 40 μm at the centre of the spray to 90 μm at the outer edge. Figure 3 shows cumulative undersize distributions at two different radial positions: the centre of the spray and the outer edge (36 mm radius). The overall distribution through the spray, plotted on a cumulative volume basis, is also shown in Figure 3. The relative span, $(D_{vo.8} - D_{vo.2})/D_{vo.5}$, is also plotted in Figure 2 showing that the central portion of the spray, out to a radius of approximately 18 mm, is rather broad with a relative span of ~1.0. Outside this region the relative span drops sharply to a value of ~0.4 at a radius of 36 mm, indicating a narrowing of the distribution with increasing mean size. The local spatially averaged volume concentrations of liquid droplets at different positions across the spray are plotted in Figure 4. The results are normalized by the peak value where the measured volume concentration is 8.7×10^{-2}% by volume.

The spray was also studied under the same conditions using the standard Malvern laser diffraction instrument to measure the overall scattered light power distributions for a series of scans in which p was varied, firstly in 4 steps of 9 mm from the spray centre and secondly in 14 steps of 3 mm. This variation of step size (Δp) provided information on the optimum spacing of scans. These line-integrated data were transformed numerically into distributions within the spray by using the transformation routine described in Section 2. Particle size distributions were derived from the scattered light distributions by solving Equation 4 using two alternative iterative techniques. The two techniques[7] used were: (i) to obtain a best fit to the data by assuming a Rosin-Rammler size distribution, and (ii) to obtain the droplet volume concentrations in 15 size ranges of the size distribution which gave the best fit to the light distribution (the 'Model Independent' solution). The size distributions at different radial positions were found to be in satisfactory agreement with the Rosin-Rammler distribution and there were no major differences between these distributions and those obtained using the Model Independent technique. Thus only the Rosin-Rammler data are reported here.

Figure 2 compares the photographic data for volume median diameters and the relative span, with that obtained from the tomographically transformed scattered light. There is seen to be excellent agreement between these two sets of results. Significantly better agreement is obtained when the short (3 mm) steps are used rather than the long (9 mm) steps in p. This improvement was noted throughout the data obtained. Photography, as for all particle sizing techniques, is liable to possible inaccuracies. However, spray conditions where these occur can generally be recognized in photographs, and it is therefore reasonable to use these photographic measurements as reference data. Results obtained by tomographic data transformation are also included in Figure 3 where the cumulative size distributions are presented. There is excellent agreement for the outer edge data throughout the size range, however the central and overall curves both show a discrepancy at the lower end. From these two curves it can be seen that the light diffraction technique indicates that there is of the order of 5% of the spray below 10 μm whereas the photographic data shows no droplets below 10 μm. However the photographic technique becomes less reliable once droplets below ~15 μm are encountered due to resolution problems and it is considered that the light diffraction data is more reliable in this size range. This is borne out by the fact that this effect is only noted when there is a significant volume of droplets below 25 μm and not in the coarser distribution observed at the outer edge of the spray.

The total light power falling on the detector can be related to the volume concentration of droplets in the beam if the drop size distribution is known. This gives a relative volume concentration which is related to the true concentration by a constant determined from the optical system. In the absence of this constant the concentration obtained is normalized with respect to its peak value and is plotted in Figure 4 showing excellent agreement with the photographic data.

In the second set of experiments a twin-fluid atomizer was used to give a narrow angle spray, consisting of a narrow jet of liquid injected axially into a narrow annular air jet. The spray thus produced was introduced axially into a co-flowing secondary air stream which is capable of being heated up to 400°C and of which the velocity and turbulence could be varied (Fig. 5). The whole system could be moved relative to the laser beam both horizontally and vertically, the spray being ejected vertically downwards. The results reported here were obtained for three axial planes 45, 95 and 145 mm below the atomizer both at a secondary air temperature of $20^{o}C$ and $150^{o}C$. The liquid used was kerosene, flow rate 1.5×10^{2} mm^{3}/s, the atomizing air flow rate was 6.8×10^{4} mm^{3}/s, and the secondary air flow rate was 4.8×10^{-2} m^{3}/s through a 75 mm diameter orifice.

This spray was studied using the Malvern laser diffraction instrument using a modified beam expander unit which gave a beam of 2 mm diameter. The overall scattered light power distribution was measured for a series of scans in which p was varied in steps of 2 mm. These line integrated data were transformed as before and the droplet size distributions were calculated, again using the Rosin - Rammler function. Relative volume concentrations are also calculated as before.

The volume median diameters and relative span factors are plotted against radial position for each plane in Figure 6. This shows that the spray in cold air consists of a broad size distribution at the centre which changes to a narrower distribution with a larger mean size as the outer edge is reached, thus showing that the air flow deflects the smaller particles towards the inside of the spray leaving an outer cone of larger droplets which are not deflected.[8] The overall size distribution of droplets does not significantly change from plane to plane, with axial distance along the spray. However there is a marked change in the radial distributions of size distribution from plane to plane. The values for the spray with hot secondary air are also presented for planes 1 and 2 in Figure 6. However, the signal strength at plane 3 was insufficient to allow calculation of size distribution or volume concentration thus indicating that the majority of droplets had evaporated. These results show that there is only a slight change in the volume median diameter in both of these planes whereas the span of the distribution is greatly reduced, thus indicating the disappearance of the smaller drops due to evaporation.

The relative volume concentrations are plotted in Figure 7 for all three planes in the case of ambient secondary air and for planes 1 and 2 for hot secondary air for the reason stated above. In the non-evaporating case the concentration falls with increasing axial distance and the spray diverges. In the evaporating case the concentration is seen to fall steadily relative to the non-evaporating value as axial distance is increased. Insufficient drops were detected from plane 3 to allow size distributions or concentrations to be calculated indicating that most of the drops had evaporated. An interesting feature of the results in plane 1 is that a cold cone is still observed where evaporation has not occurred significantly, but this has disappeared by plane 2.

The above results form only the initial stages of a detailed mapping of droplet size and concentration in an evaporating spray which will be carried out in conjunction with local measurements of velocity and temperature. These measurements will allow us to build up a complete picture of the local spray structure under evaporating conditions which is of great importance in calculating evaporation rates and modelling the combustion of fuel sprays.

5. Conclusions

A method of transforming line of sight light scattering data to yield measurements of drop size distribution and concentration in volume elements within the spray (tomography) has been described. The technique was investigated using an axisymmetric spray generated by a twin-fluid atomiser and the results obtained compared with those from a parallel photographic study. The good agreement obtained shows that the technique can provide information on local spray structure comparable to that from photography, with substantially reduced experimental time. The technique has been used to investigate the structure of a fuel spray both at room temperature and under vaporizing conditions in a hot air stream, and the changes in droplet sizes and volume concentrations accompanying vaporization are measured.

Acknowledgements

Support for this research work is provided by contracts with the NASA-Lewis Research Center, U.S. Air Force (AFOSR), U.S. Navy (SQUID), U.S. Army and the Science Research Council (U.K.). Thanks are due to Malvern Instruments for the loan of equipment and to Dr. David Taylor for his assistance.

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Figures

S :	Distance Along Light Beam Measured From Entry Point of Spray
P_o :	Incident Light Power Measured at Entry to Spray
P_L :	Residual Light Power in Beam at Exit From Spray

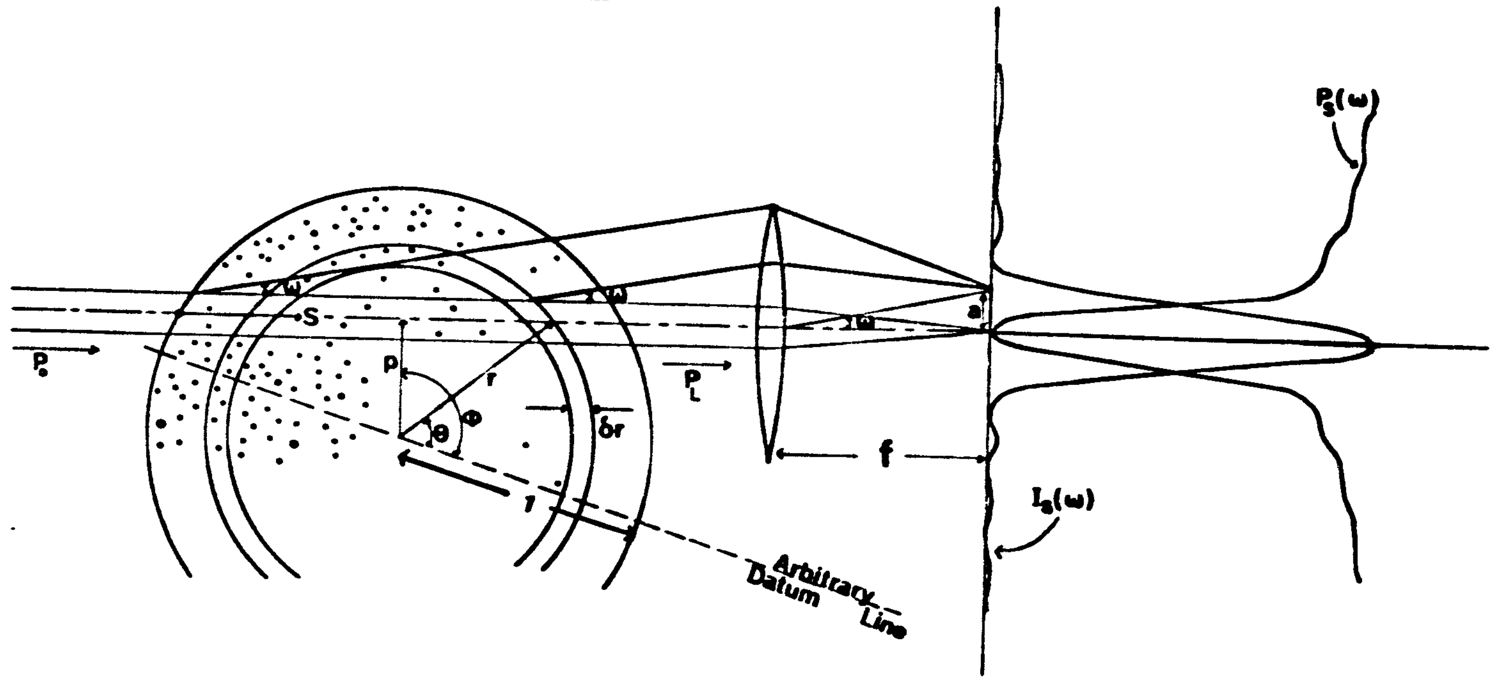

FIGURE 1 Light scattering diagram for light beam Passing through spray

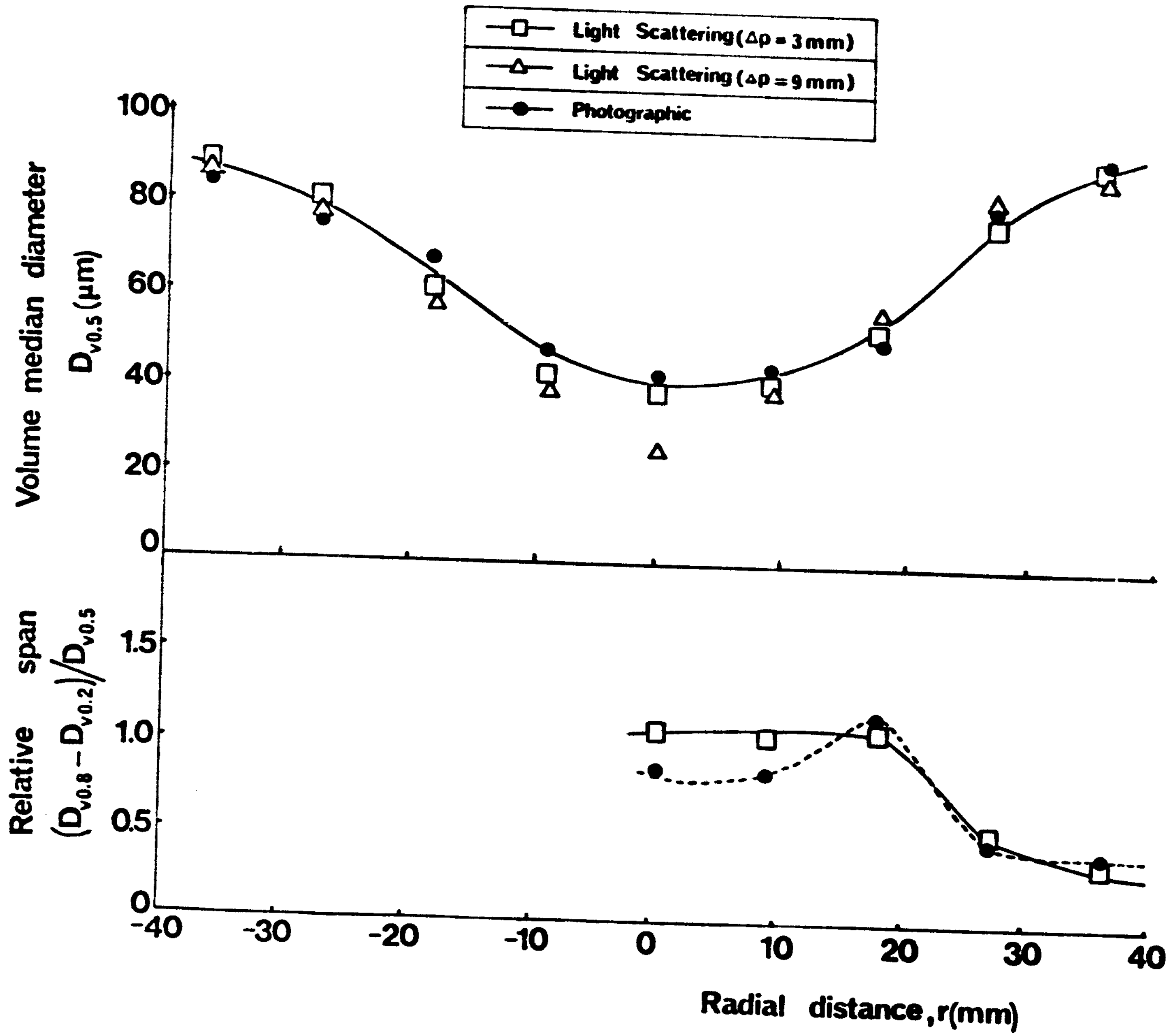

Figure 2 Comparison of droplet mean diameters and span of size distributions measured by laser tomography and photography.

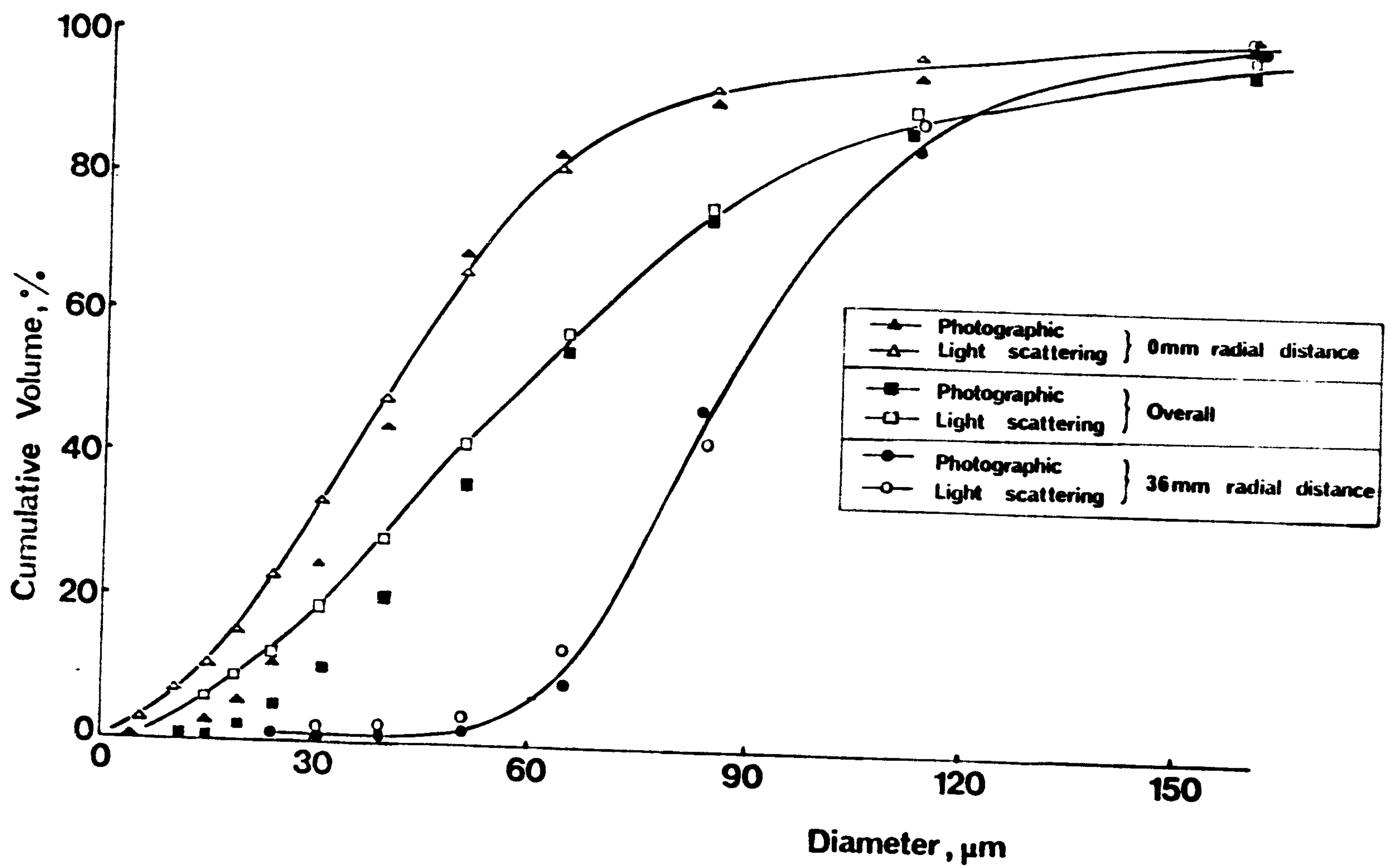

Figure 3 Comparison of cumulative size distributions measured by laser tomography and photography.

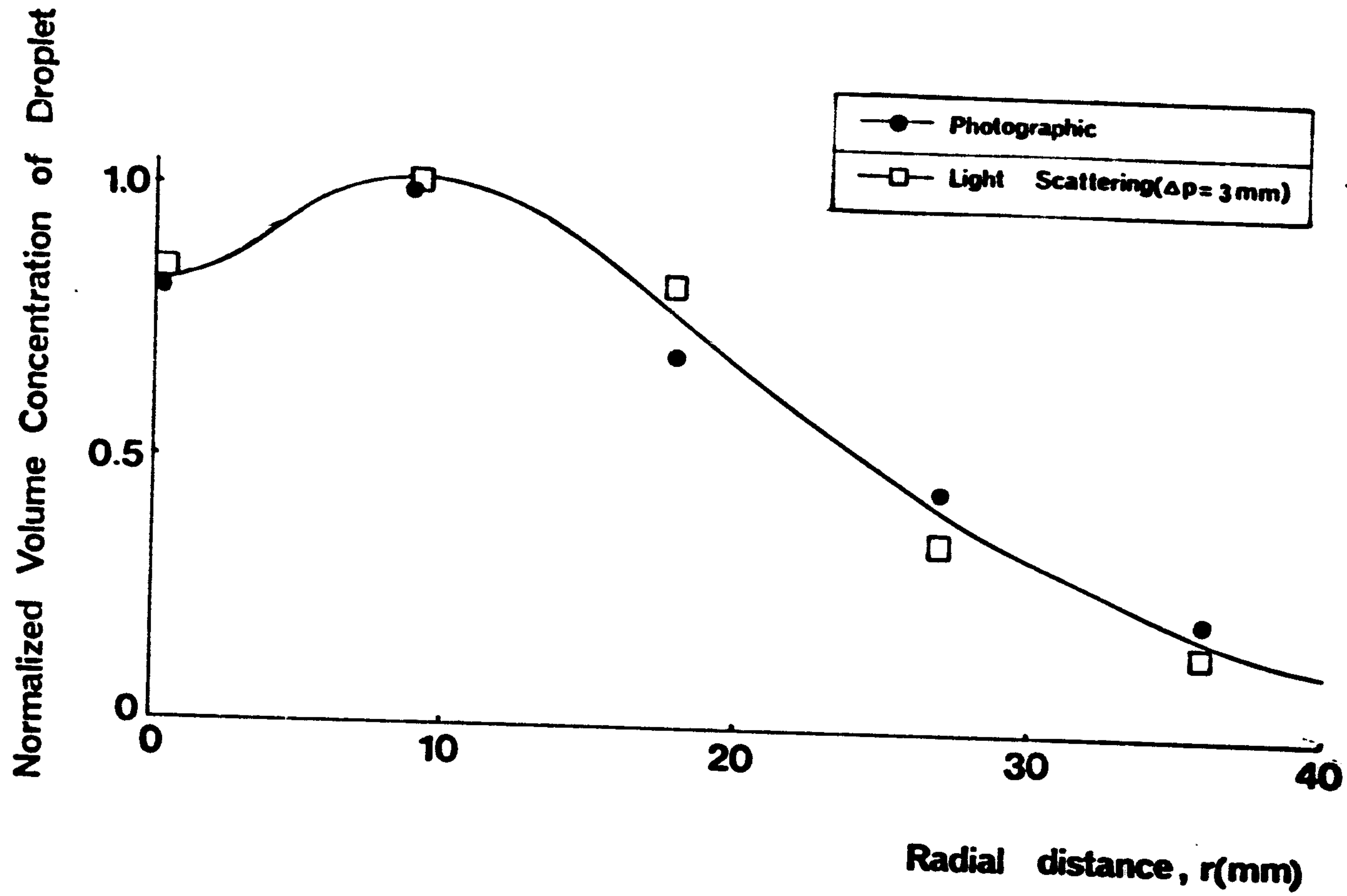

Figure 4 Comparison of droplet volume concentrations measured across spray by photography and laser tomography.

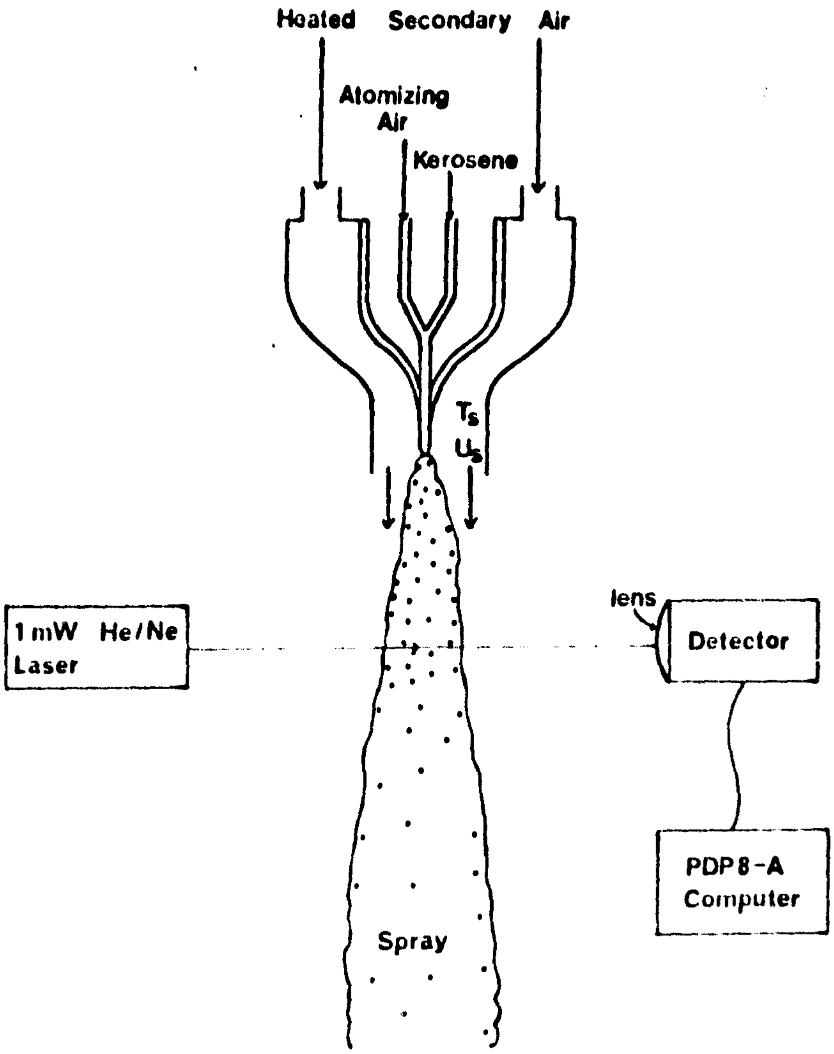

FIGURE 5 Apparatus for investigation of fuel spray vaporizing in hot air stream

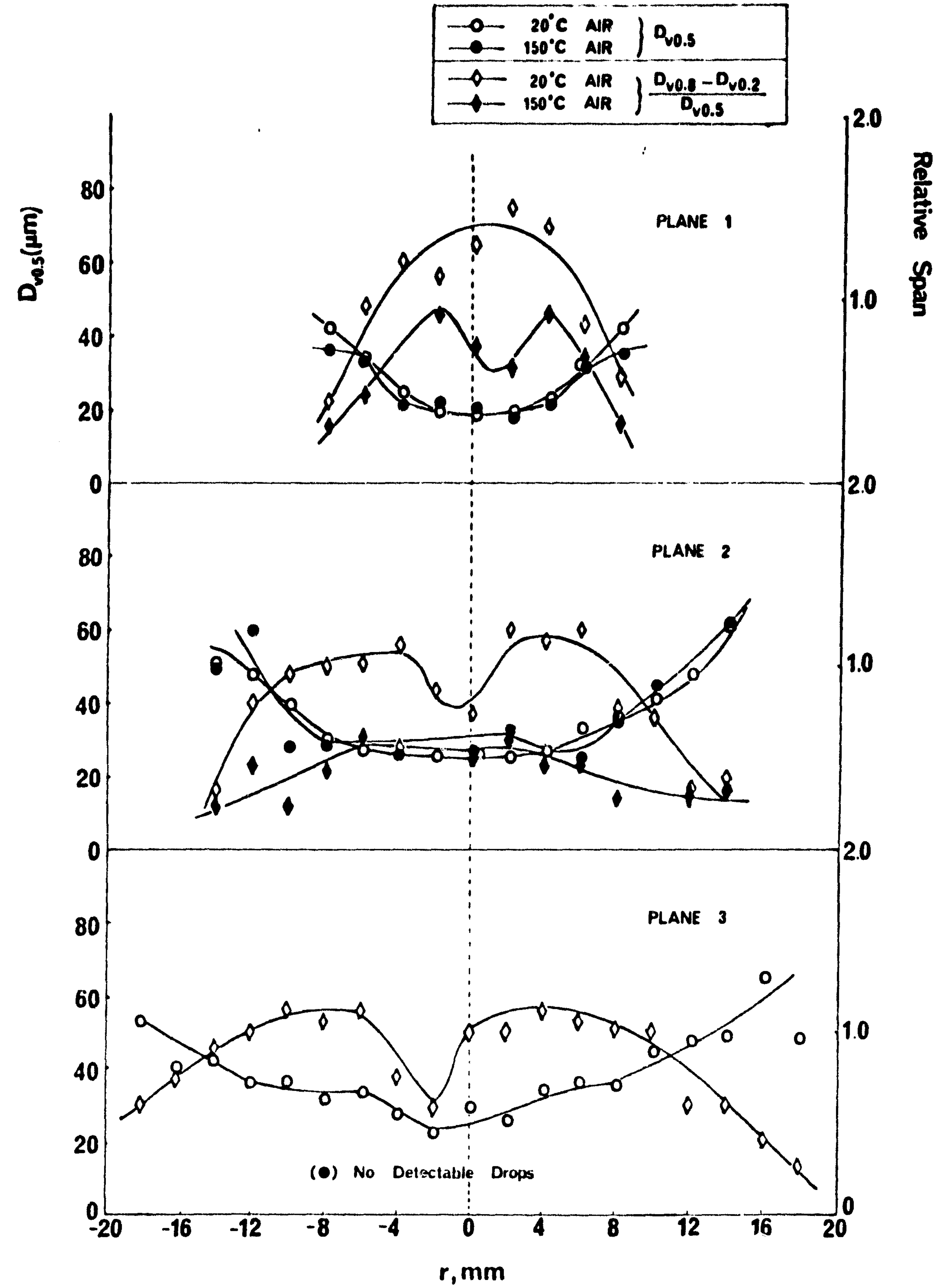

Figure 6 Laser tomography measurements of mean drop sizes and size distribution spans in kerosene sprays in ambient and heated air.

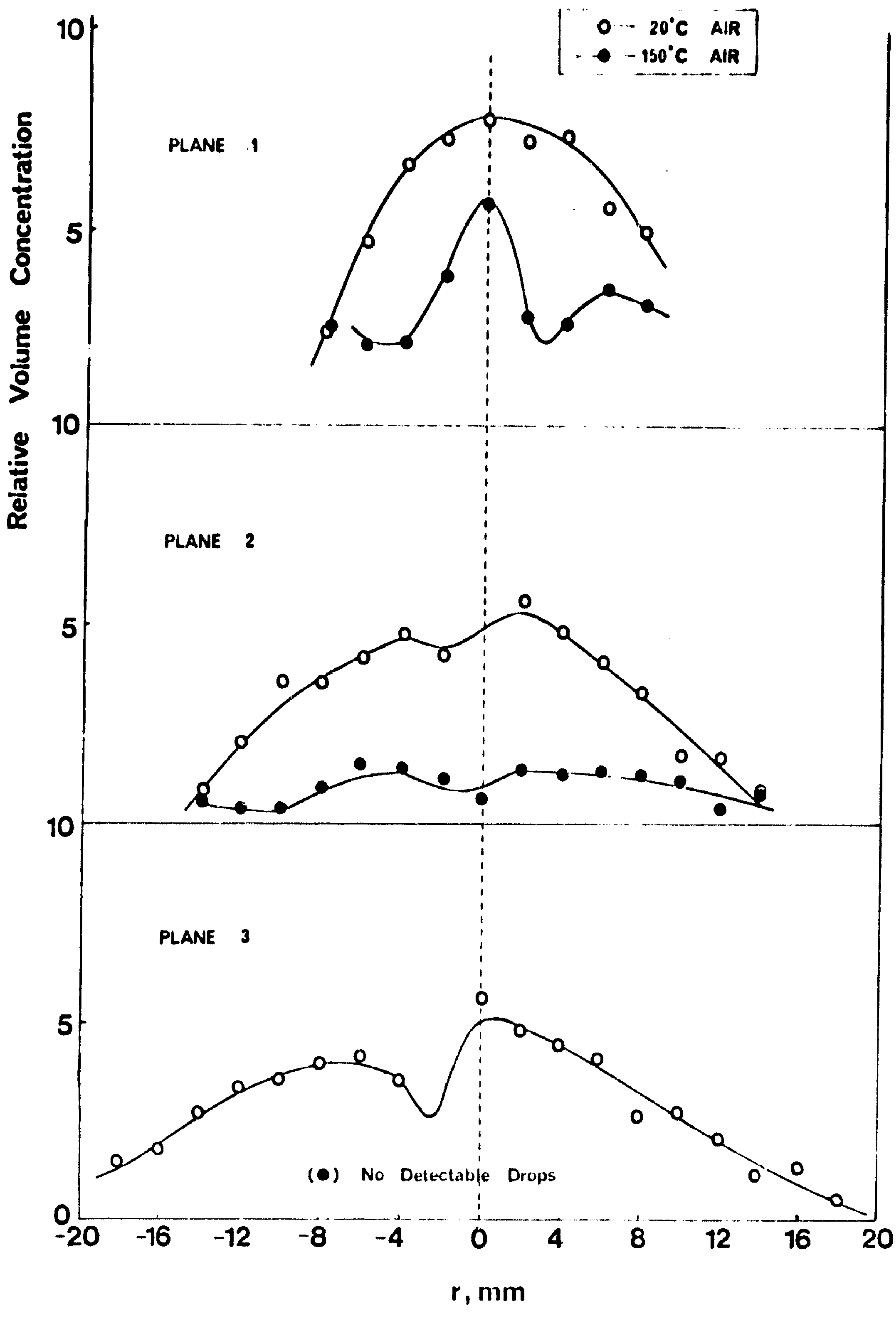

Figure 7 Local spatially averaged volume concentrations of droplets in kerosene sprays in ambient and heated air.