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IMAGE ANALYSIS OF PARTICLE FIELD BY MEANS OF

COMPUTED TOMOGRAPHY

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AABSTRACT

In order to visualize and investigate spray structures, computed tomography technique is applied to analyse droplet information. From the transmitted light intensity through the spray and/or the data of particle size distribution obtained from a Fraunhofer diffraction principle, the quantitative volume of spray droplet or local particle size was calculated and the reconstruction of spray structures was made.

This paper describes the background of computed tomography and some experimental results of the structure of intermittent spray such as diesel spray.

1. INTRODUCTION

In order to visualize and investigate spray structures, non-intrusive measurement technique has been studied. From the

transmitted light intensity through the spray, a qualitative information of droplet size and their number density will be expected. For this purpose a compueted tomography technique was introduced (Ref. 1), and the reconstruction of spray structures was made (Ref. 2).

Visualization technique is wanted for studies in heat transfer and mass transfer, and particularly, for vaporizing process in hot spray (Refs. 3, 4). During recent years, it has come to receive a large amount of attention to these field, but we can not find out any paper on visualization of vaporizing phenomena of spray.

This computed tomography method will be applied to analyse the droplet size distribution of spray such as industrial atomizer, disel nozzle and so on. And it will contribute to analyse on hologram.

This report presents the background of computed tomography and some experimental results of spray structure of intermittent injection such as diesel nozzles.

2. BACK GROUND OF COMPUTED TECHNOLOGY

As shown in Figure 1, let a coordinate system fixed on the subject be (x,y), and a coordinate obtained by rotating the former through degree θ be (X,Y). When a beam parallel to this Y axis and with an intensity of Io is made to impinge on an object with light absorption coefficient distribution of f(x,y), the intensity of light after transmitting through such an object is given by Equation 1.

$$I/I_0 = \exp\left[-\int_{-\infty}^{\infty} f(X\cos\theta - Y\sin\theta, \ X\sin\theta + Y\cos\theta)dY\right] \quad \cdots \cdot (1)$$

The logarithmic transformation g(X,θ) of this attenuation rate is called "Projection Data", which is represented by Equation 2.

$$g(X, \theta) = \int_{-\infty}^{\infty} f(X \cos \theta - Y \sin \theta, \ X \sin \theta + Y \cos \theta) dY \quad \cdots \cdots \ (2)$$

By determining this X value from $-\infty$ to $+\infty$, one-dimensional projection data is obtained. Let us then determine this one-dimensional projection data for the range of $0 \leq \theta < 2\pi$. There are two main methods to reconstruct tomograms from the projection data so obtained, namely the iterative method and the analytical method. In the former method, projection data generated from estimated absorption coefficient distribution is compared with that measured for sucssecive correction. In practice, the analytical method is more widely used because of less calculation time requirement and the higher accuracy it offers. One of the simplest yet strict analytical methods is the Fourier transformation method. Fourier transformation $F(\xi, \eta)$ of f(x,y) when expressed by polar coordinates gives Equation 3.

$$F(\omega \cos \theta, \omega \sin \theta) = \int_{-\infty}^{\infty} g(X, \theta) \exp(-i\omega X) dX \quad \cdots \cdots \cdots \cdots \cdots (3)$$

Therefore, f(x,y) can be determined by Fourier inverse transformation of $F(\xi, \eta)$. A mathematical equivalent method is to perform Fourier inverse transformation of Equation 3 on polar coordinates to obtain Equation 4.

$$f(x, y) = 1/(8\pi^2) \int_0^{2\pi} \left[\int_{-\infty}^{\infty} F(\omega \cos \theta, \omega \sin \theta) |\omega| \exp(i\omega X) d\omega \right] d\theta \quad \cdots (4)$$

Namely, by applying a filter function expressed as ω to $F(\xi, \eta)$ and superimposing by inverse projection, the image is reconstructed. This method is called "Filtered back projection method" (Ref. 5). By convolution of Fourier inverse transformation h(X) of this filter function in the original region, Equation 4 can be transformed into Equation 5.

$$f(x, y) = 1/(4\pi) \int_0^{2\pi} \int_{-\infty}^{\infty} g(X', \theta) h(X - X') dX' \, d\theta \quad \cdots \cdots \cdots \cdots (5)$$

This method is called "convolution method" (Ref. 6), which is adopted in the present work.

The filter function ω diverges as $|\omega|$ increases and hence the equation does not lend itself to strict calculation. Therefore, it is necessary to attenuate this function in regions where ω is large. Various filter functions have been proposed.

Let the sampling number in X direction and the number of rotational movements be M and N respectively for each equation. Then, a determinant with MxN matrix $G(X, \theta)$ and MxN matrix H can be obtained as indicated by Equation 6.

$$Q(X, \theta) = H \cdot G(X, \theta) \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \quad (6)$$

This equation is to calculate inverse projection and takes as f(x,y) the sum of q(X,θ) for all θ relative to the point (x,y) of interest. However, q corresponding to the point (x,y) is not necessarily on sample point of q(X,θ) and in such case, interporation is made using sample points at both ends.

Figure 2 shows the flow chart of the calculation in computing. The measured projection data then undergo matrix calculation with

precalculated and filed filter function matrix. By back projection of the resultant q(X,θ), f(x,y) is obtained, which is displayed according to the display conditions that can be set s desired.

Generally, it is said that transformation of filter functions for correction of projection data used in Equations 5 and 6 has significant influence on quality of the reconstructed image. In this work, the modified filter function of modified Shepp and Logan (Ref. 7) which is the commonest is used.

Of course, the more samplings there are and the greater number of rotary movements, the higher is the quality of reconstructed image, but a compromise must be found because of limitations, such as measuring instrument accuracy, resolution, computer memory size, CPU time etc. This work deals with liquid spray particles which are macroscopically stable both in time and space, but when a small portion is considered, each particle is constantly moving and hence it is necessary to average them to some extent in time and space for data sampling. Thus, it serves no purpose to attempt to improve the sampling resolution more than necessary. In view of this image quality and time for computation, it was decided to select 61 sample points(reconstruction image pixels 61 x 61) and 30 rotary movements with 6 degree increments, which are also considered industrially applicable. In this work, measurement is done based on these coditions.

3. EXPERIMENTAL APPARATUS AND METHODS.

3.1 Experimental apparatus

In order to visualize and analyse the spray structure and estimate the spray particle size or their spatial density, the

distribution of the transmitted light intensity was measured, and the reco nstruction data of spray was calculated by CT technique, respectively.

The transmitted light intensity is pictured by 35mm photo or detected by TV camera (Type C-1000, Hamamatsu TV) which is controlled by small comuter (LSI 11/23: DEC). The reconstruction of pictures of spray was displayed on CRT (NEXUS 5500: Kashiwagi Lab.) or X-Y plotter.

Fig. 3 shows a block diagram of the hardware utilized in this study. Images are created by dierect imaging of a spray sample area on a high resolution visicon camera. This camera has a resolution of 8 bit and 1024x1024 pixecels.

3.2 Application of Computed Tomography to sprays

Assume a particle group with n particles of diameter D in unit volume. Then, the attenuation of parallel incident light caused by such a group is given by Equation 7.

$$I/I_0 = exp[-RK_t(\pi D^2/4)nl] \quad \cdots\cdots\cdots\cdots\cdots\cdots (7)$$

where Io is the incident light intensity, I is the light intensity after passing through the particle group, Kt is the total scatter coefficient, l is the optical path length through the particle group and R is a coefficient that depends on the particle size parameter α ($\alpha = \pi D/\lambda$, where λ is incident light wave length) and optical system. The total scatter coefficient Kt is known to be nearly constant at 2 when $\alpha > 30$. In the case visible rays of λ=400 to 700nm, D>10 μm and hence α>45. As a result, Kt may be considered nearly constant. R is less influenced by α when the recieving angle is

narrower. If the receiving angle is small and particle size distribution is limited to a narrow range, R is nearly constant. Therefore, the sum of particle sectional areas 𝜋Dn/4 corresponds to f(x,y) of the Equaton 1. Thus, from the projection data obtained by this light attenuation, the density distribution of particle area on the spray section can be obtained.

4. EXPERIMENTAL RESULTS AND DISCUSSION

In order to confirm the reliability of reconstruction data by CT technique, the relations between the distribution of the transmitted intensity and the measured dispersion rate of spray were verified on the swirl chamber atomizer.

The dispersion rate was measured by one dimentional line type paternator and the reconstructed picture equivalent to dispersion rate was calculated by Computed Tomography technique, in which the data of the transmitted light intensity distribution was used.

The diameters on various point were claculated by means of two kinds of CT. They are the transmitted light energy method as above mentioned and a Fraunhofer diffraction energy distribution method by using the particle sizer (ST-2600HSD).

The reconstruction data of droplet concentration and the measured value of dispersion quantity are shown in Fig. 4. These results were normalized by their maximum amount, respectively. This calculated concentration is called as relative concentration. Judging from the figure, they are coincide with each other, and hence, this evaluation method is effective in the research of spray structures.

Applying an onion model to an axi-symmetric spray, local droplets

diameter and the droplet size distribution will be obtained in near future.

Figs. 5 and 6 show the reconstructed image data of disel spray. Pusudo colour maps corresponding to the concentration of paricles are pictured. As well known, disel spray injection is a kind of intermittent one, so instantaneous data which were taken during the exposure time of 75 nano second.

Fig.5 shows the spacial spray concentration injected from throttle nozzle at 1.1 ms after opening injection and each reconstructed image photo shows the data of cross section at the positions of 10, 20, 30, and 40mm from nozzle. Fig.6 presents the data of spray particle density change with time at 30 mm position from the nozzle tip. Comparison of Figs. 5 and 6 indicates that with diesel spray, later sprayed particles catch up with and overtake preceding particles.

On observing the phenomena of the diesel injection, they are complex and non-steady, so we need to develop new measuring equipment for particle size and its distribution. For example, it is a automatic data reduction system from hologram. We are now undergoing to develop and fabricate prototype of automated data reduction system with auto focus and stage system.

5. SUMMARY

A novel visualization method of spray structure was presented and the pictures of the internal strucures of swirl chamber atomizer and disel injection spray atomizer were reconstructed by Computed Tomography technique.

This method is useful for qualitative estimation of spray structure and particularly, for visualization of evaporation and/or combustion phenomena of particles.

6. AKNOWLEDGEMENT

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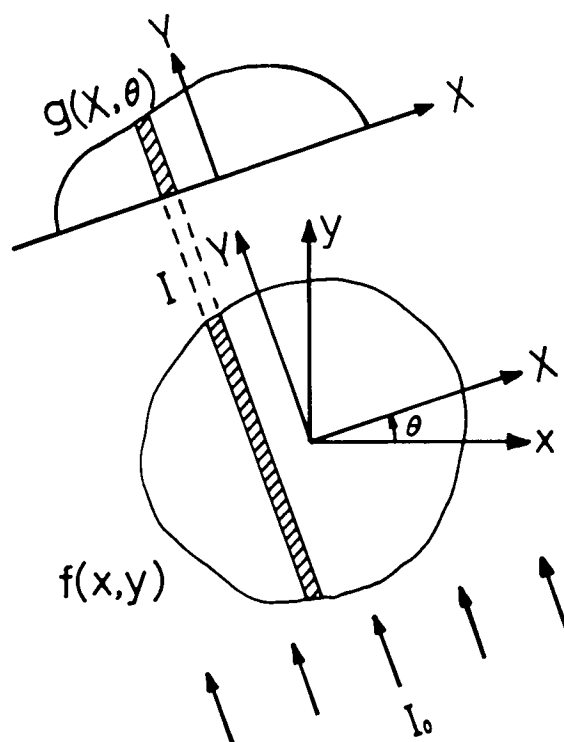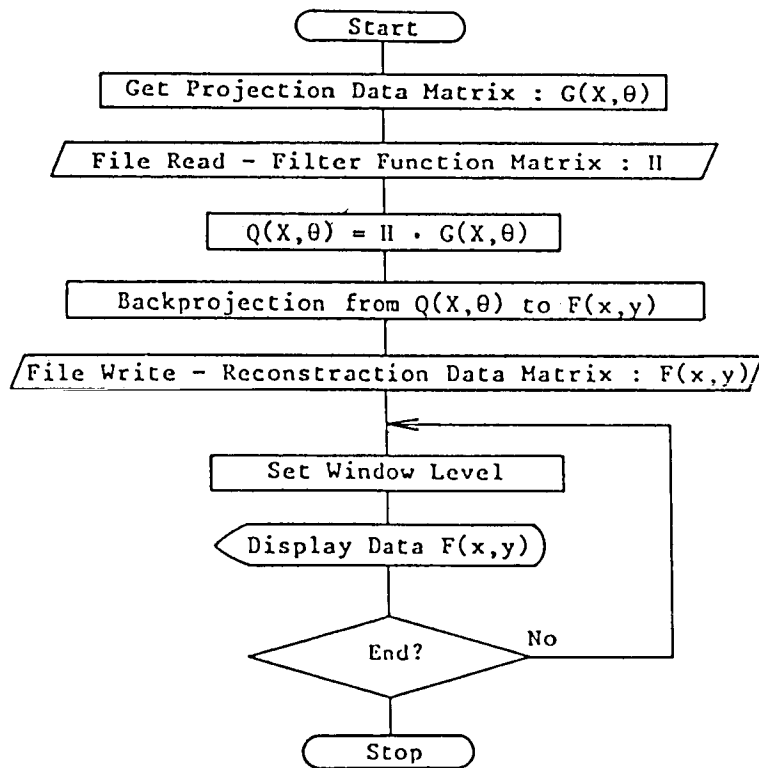
Fig.1 Prjection data g(X, θ)

Fig.2 Flow chart of data reduction

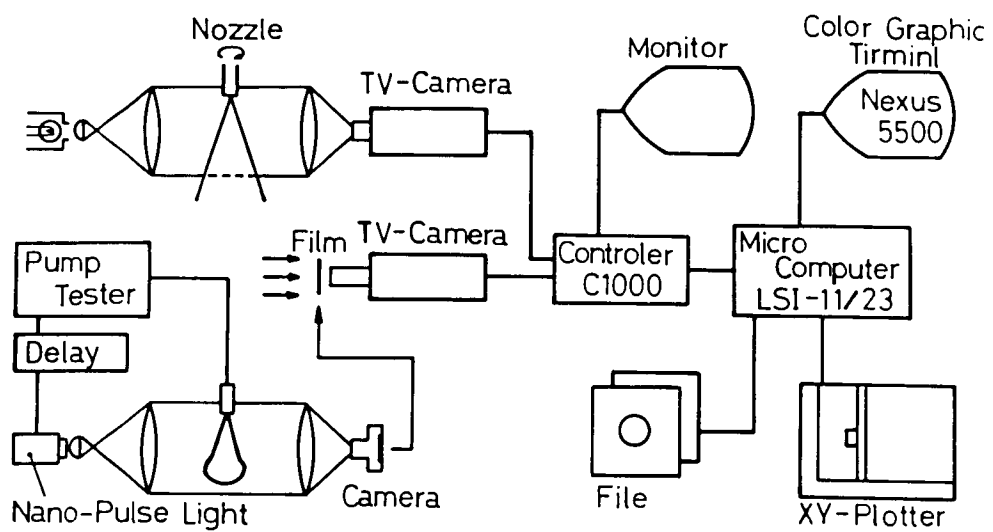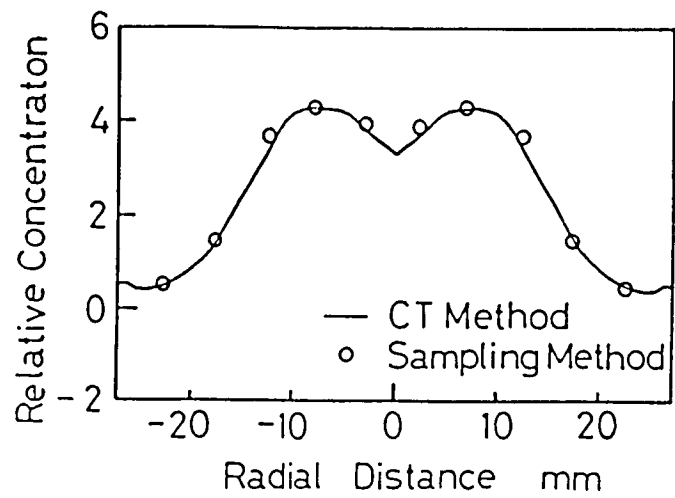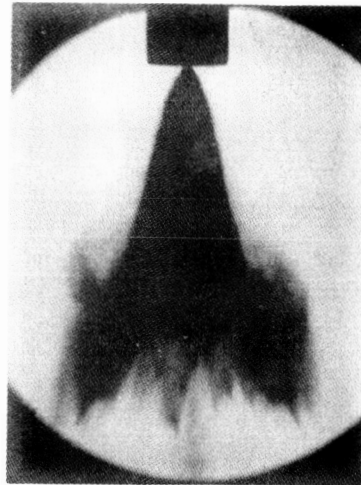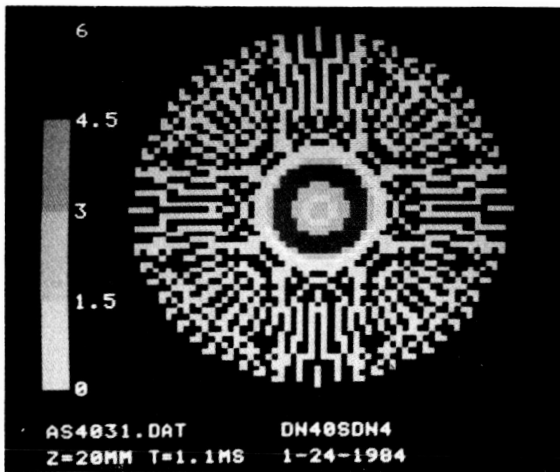Fig.3 Equipment block diagram

Water: P=1.08MPa Ta=293K
T_l=287K Q=1.76x10^{-6}m^3/s

Fig.4 Comparing between CT and sampling method on
relative spacial concentration

ORIGINAL PAGE IS
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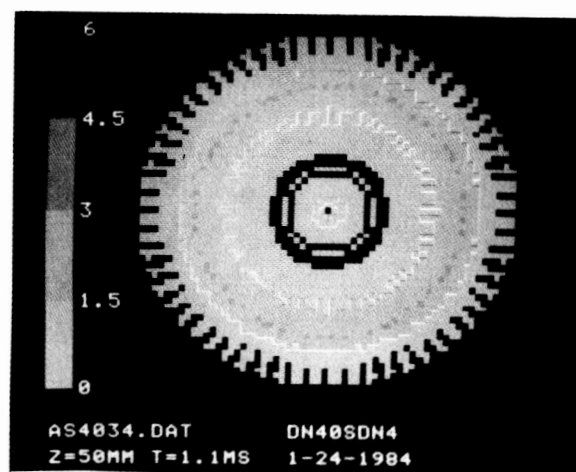Z=40MM T=1.1MS   1-24-1984

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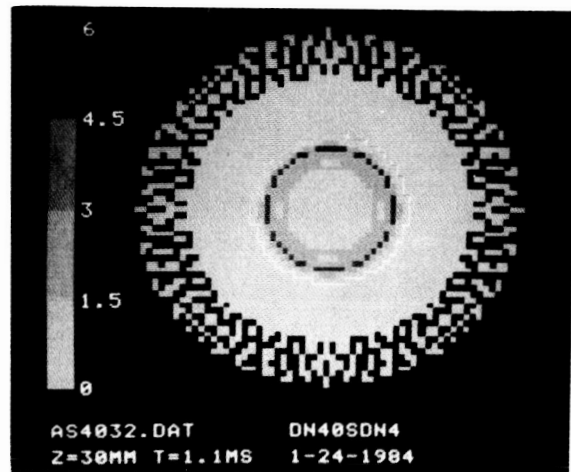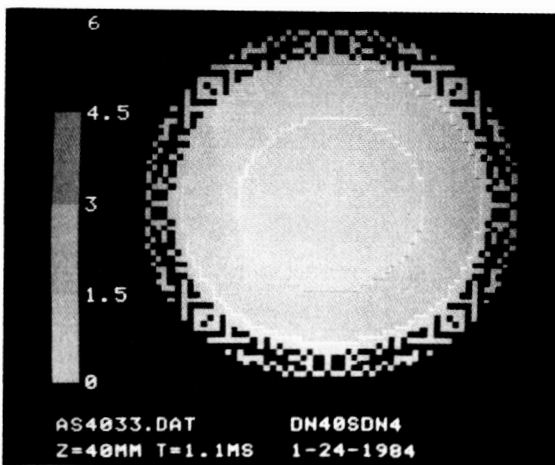
50 mm

Fig.5 Image of diesel spray structure by Computed Tomography
Psudu color corresponding to spray concentration
(Throttle nozzle for Diesel Engine)

0.9 ms

1.3 ms

1.7 ms

2.1 ms

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Z=30MM T=0.9MS   1-24-1984

AS4042.DAT   DN40SDN4
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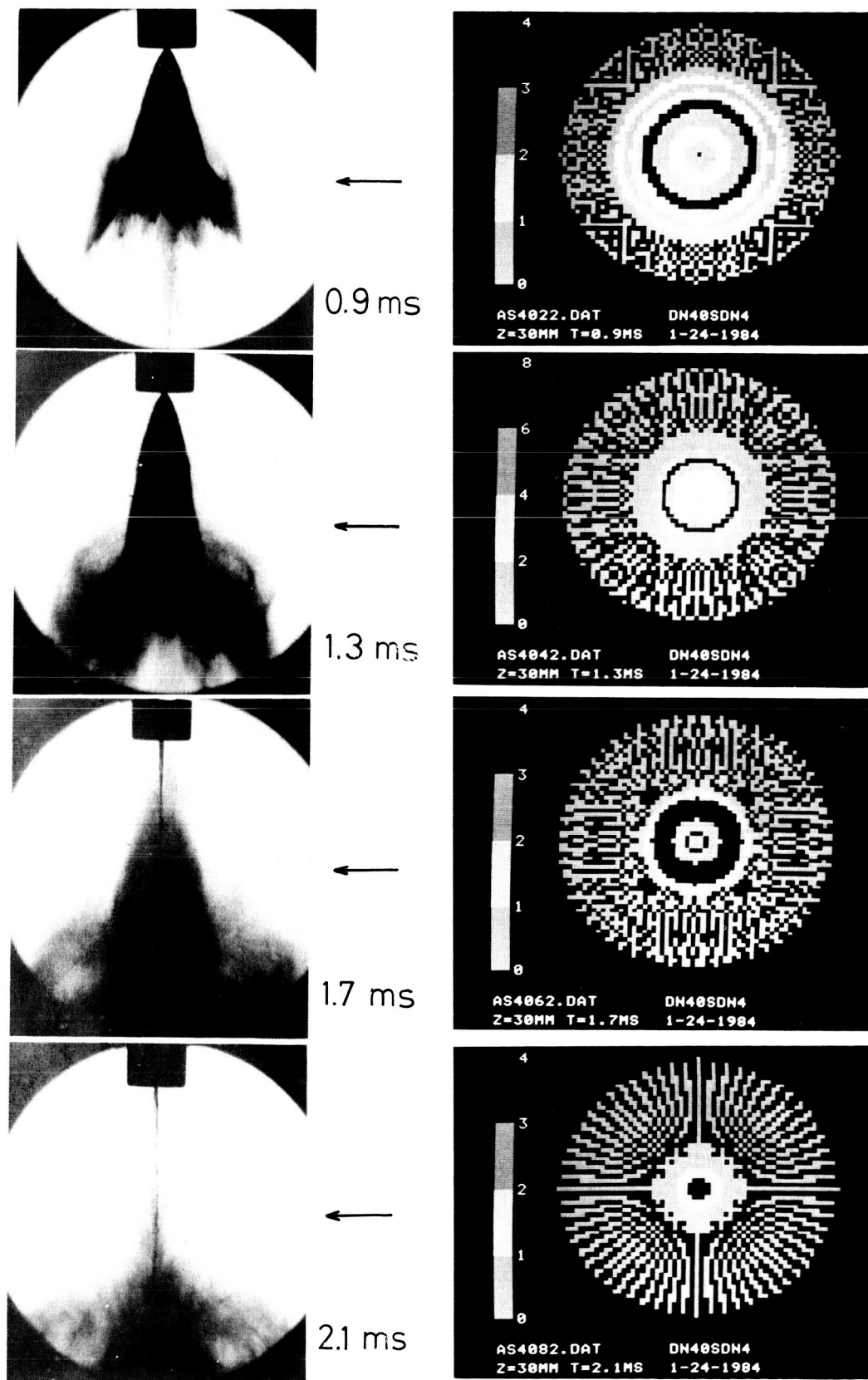Z=30MM T=2.1MS   1-24-1984

Fig.6 Time dependence of spray density distribution
       by CT method
       (Throttle nozzle for diesel engine)

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