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Ramy El-Emam
*Mechanical Power Engineering Department., Faculty of Engineering., El-Mansoura University., Mansoura., Egypt.*

A. Desoky
*Mechanical Power Engineering Department., Faculty of Engineering., El-Mansoura University., Mansoura., Egypt.*

M. Tolba
*Mechanical Power Engineering Department., Faculty of Engineering., El-Mansoura University., Mansoura., Egypt.*

K. El-Nahhas
*Mechanical Power Engineering Department., Faculty of Engineering., El-Mansoura University.,Mansoura., Egypt.*

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# LIQUID SPRAY CHARACTERIZATION USING PHASE/DOPPLER TECHNIQUE

## تحديد خصائص السوائل المذررة باستخدام تقنية طور دوبلر

S. H. EL-EMAM, A. A. DESOKY, M. A. TOLBA, AND K. E. EL-NAHHAS
MECHANICAL POWER DEPT., FACULTY OF ENGINEERING
MANSOURA UNIVERSITY, MANSOURA, EGYPT.

## ملخص البحث:

في هذا البحث تم إعداد تختة اختبار لتحديد خصائص التذرير للماء ووقود الديزل والكيروسين أثناء رشها رأسيا لأسفل باستخدام رشاش ضغط دوامي خلال أنبوب ذي مقطع مربع الشكل ومزود بمروحة سحب في نهايته وذلك باستخدام تقنية الليزر. تم تزويد تختة الاختبار بمنظومة لتحريك الرشاش رأسيا وأفقيا حتى يمكن أخذ قراءات في مواضع مختلفة محددة داخل مخروط رشة السائل. حيث أجريت قياسات لتحديد كل من الحجم المتوسط للقطيرات ومتوسط سرعاتها ومعدل التوزيع العددي والحجمي وكثافة التدفق للقطيرات داخل مخروط رشة السائل.

وتشير النتائج التي تم التوصل إليها الى أن الحجم المتوسط للقطيرات يزداد وتقل السرعة المحورية المتوسطة لها كلما كانت بعيدة عن محور مخروط الرشة. كما أنه بزيادة المسافة المحورية من موضع الرشاش فإن قيم السرعة المحورية المتوسطة للقطيرات تنخفض وذلك لرشات السوائل الثلاثة المستخدمة. كما يتناقص كل من الحجم المتوسط والفيض الحجمي للقطيرات في حالة الماء ووقود الديزل المستخدم بينما يتزايد في حالة رشة الكيروسين. كما أكدت النتائج أنه مع زيادة ضغط الرش يقل كل من الحجم المتوسط والفيض الحجمي وتزداد السرعة المتوسطة لقطيرات الرشة للسوائل الثلاث المستخدمة.

## ABSTRACT

Spray characteristics of three liquids, water, diesel fuel, and kerosene, sprayed vertically downward in a transparent squared section tube which is accessed with an exhauster, through a pressure swirl atomizer, have been evaluated by means of Phase Doppler Particle Analyzer (P/DPA) system. The experimental apparatus is accessed with a traversing system which enables to make complete scan, radially and axially, for the spray cone. Different pressure differentials across the nozzle are applied to study their effect on spray characteristics. Measurements of droplet mean diameter, droplet size distribution, droplet mean velocity, liquid volume flux and droplet number density have been carried out.

Experimental results showed that the droplet size increases and droplet axial mean velocity decreases as the radial distance from spray axis increases. Also, as the axial

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distance from the nozzle plane increases, the droplet axial mean velocity decreases for the used liquids, the droplet mean diameter and liquid volume flux decrease for both water and diesel fuel but deviation is observed for kerosene, and the droplet number density increases for all used liquids. As the pressure differential across the nozzle increases, both droplet mean diameter and liquid volume flux decreases, and the axial mean velocity increases, for the used liquids. Data analysis shows that the mass median diameter to Sauter mean diameter ratio is affected by the pressure differential across the nozzle, and by Rosin-Rammler exponent, which is a measure of the width of distribution. kerosene, always, has the smallest droplet mean diameter, and water, in most of cases, has the largest mean diameter. Sometimes, diesel fuel competes water having the largest mean diameter.

## 1- INTRODUCTION

In most of liquid fuel spray combustion applications, fuel atomization is of considerable importance in combustion performance as it affects ignition, efficiency, stability, temperature distribution of the gases at the combustor exit, level of pollutants, as well as amount of flame radiation affecting the durability of the combustion liner [1 and 2]. The pressure swirl atomizer in which a swirling motion is imparted to the fuel so that, under the action of centrifugal force, it spreads out in the form of a hollow cone as soon as it leaves the orifice.

Spray characteristics depend on the properties of the liquid, i.e., mainly on its viscosity, surface tension, and density. These properties change with liquid type, and for a given liquid, with the operating conditions such as temperature and pressure. It is difficult to separate the influences of the three liquid properties when investigating the spray qualities of fuel injectors [3].

Spray characteristics and performance of a certain atomizer spray require detailed information concerning the local distribution of droplet sizes and velocities. Techniques of spray measurements have been changed dramatically in the past decade with the advent of Laser Doppler Particle Analyzer which can measure each of the droplet size and velocity simultaneously [3].

An experimental investigation of the local distribution of a pressure swirl atomizer spray has been carried out, using phase Doppler particle analyzer, by Nosier et al. [4].

They concluded that apart from the zone which is very close to the plane of injection, the radial distribution indicates that larger droplets tend to exist at the spray edge. The droplet Sauter mean diameter ($D_{32}$) decreases with downstream axial distance.

Brena de la Rosa et al. [5], have presented measurements of the droplet size and droplet velocity distributions, particle number density, volume flux and angle of trajectory for a pressure swirl atomizer sprayed into a low swirling field. The spatial distribution of sizes and velocities, particle number density, and volume flux of the spray are strongly influenced by the dynamics imposed by the swirling field.

The aim of this study is to analyze spray characteristics, such as droplet mean diameter, droplet size distribution, droplet mean velocity, liquid volume flux, and droplet number density, of a pressure swirl atomizer using the Phase Doppler Particle Analyzer. The study includes the effects of the nature of the atomized liquid and the injection pressure on the different parameters of spray characteristics.

## 2- EXPERIMENTAL APPARATUS

An experimental apparatus has been designed to investigate the atomization characteristics of a pressure swirl atomizer spray. A schematic diagram of the experimental apparatus is shown in Fig. (1). It consists of the injection system, the test section with an exhauster, and the instrumentation.

The pressure swirl atomizer used in the present work was supplied by Delavan INC. and has the following specifications: nominal spray cone angle = 60° , orifice diameter = 1 mm, nominal flow rate = 7 $cm^3/s$, and number of tangential ports 4. A pressure vessel (60 cm dia., 80 cm length) is used as the facility to pressurize the liquid. The lower part of the vessel volume is occupied by the liquid and a compressed air fills the upper part. The injection pressure, monitored by a pressure gauge, can be increased by opening the compressed air inlet valve and closing the vent valve. The liquid supplied to the injection nozzle is metered by a calibrated metering tube.

In order to meet the requirements of more smoothly measurements, the transmitter and the receiver of the phase Doppler particle analyzer has been steadfastly held. Therefore in order to give a spatial mapping of the particle size distribution, the apparatus is provided with a traversing system. A transparent test section is designed to be large enough to avoid droplets accumulation on its sides to prevent obstruction of Laser beams travel. An exhauster is mainly used to draw the vapor and very small droplets, which tend to recirculate after escaping from the principal spray cone and distorting its shape.

## 3- PHASE DOPPLER PARTICLE ANALYZER

The Phase/Doppler anemometer used in this study is a dual-beam phase Doppler particle analyzer (P/DPA) supplied by Aerometrics INC. The principles of the Phase/Doppler anemometry, utilizing the dual beam optical mode shown in Fig. (2), have been reported previously by Bachalo and Houser [6]. The instrument consists mainly of the transmitter package, the receiver package with detectors, a signal processor, and an IBM microcomputer The transmitter package consists of a low power He-Ne laser operating at a wavelength of 0 6328 micrometers, a beam splitter which allowed for a variable beam separation, and a transmitter lens. The beam splitter produces two parallel beams which are caused to intersect by the transmitting lens. The beam crossover is the point at which measurements are made and is referred to as the "probe volume". The receiver package is comprised of a lens assembly which collects light scattered by droplets within the probe volume and focuses it onto a pinhole. Light which has passed the pinhole is directed by mirrors to the detectors The IBM PC microcomputer was programmed to accept the digital signals and manipulate the data from the signal processor.

## 4- RESULTS AND DISCUSSIONS

### *4-1: Droplet Size Distribution*

Frequency distribution curves, based on temporal distributions, which may be regarded as a characteristic of the spray, can be plotted from the droplet size histogram. Droplet size distributions at different axial positions ( X/d = 30, 90, and 150, where X is the axial distance from the nozzle plane and d is the atomizer orifice diameter which equals 1 mm) on water spray axis are shown in Fig. (3). In general, size distribution follows a normal distribution curve whose peak is shifted up with increasing the axial distance from the nozzle. Also, the results reveal that as the pressure differential increases, the distribution is narrower and the peak is shifted up. Similar results were obtained by El-Emam. [7], using the histogram results of droplet counts from the photographed images.

Figure (4) shows droplet size distributions on the spray axis for water, diesel fuel, and kerosene sprays It is noticed that, for the mentioned conditions, the frequency of small droplets is the highest for kerosene and is the smallest for water. The vice versa is that the frequency of large droplets is the highest for water and is the smallest for kerosene. Similar results are obtained and reveal that the kerosene spray has the smallest droplet mean diameters in all cases. On the otherhand, in most cases water has the largest droplet mean diameter, however, diesel fuel sometimes competes water having larger droplet mean diameters.

Droplet size distributions of pressure swirl nozzles have been extensively studied by Simmons (quoted from [3]). He suggests that the droplet size distribution of a well-designed swirl atomizer can be calculated with only the mass median diameter, MMD ($D_{50}$), or the Sauter mean diameter, SMD ($D_{32}$), of the spray given. A fixed relationship between the MMD ($D_{50}$) and SMD ($D_{32}$) is observed from a large number of tests on both pressure swirl and air-blast atomizers, which showed that MMD/SMD = 1.2. Wittig et al. [8] observed considerable deviations from Simmons experimental results and illustrated theoretically that the ratio MMD/SMD is strongly dependent on the width of distribution. Also, the mathematical Rosin-Rammler relationship between the cumulative volume fraction and droplet size, which is $v = 1 - \exp[-(D/x)^k]$ where $v$ is the fraction of the total volume contained in droplets of diameter less than $x$, is used in a wide range, to describe droplet size distribution of swirl nozzle. The exponent, k, which determines the width of the distribution about the diameter D has been found to be a function of the pressure differential, ΔP, across the nozzle [3]. Figure (5) shows the relationship between the $D_{50}/D_{32}$ ratio and Rosin-Rammler exponent, k, which indicates the dependence of k on the width of distribution which agrees with the results of Wittig et al. [8].

### *4-2: Droplet Mean Diameter*

The droplet mean diameter can be described by a variety of definitions varying according to the purpose for which it is used. The Sauter mean diameter ($D_{32}$) is considered as an important index in combustion studies as its includes the droplet surface area and volume indication which are of primary importance for evaporation calculations.

Therefore, the mean diameter in this study is predominantly presented by $D_{32}$, (SMD) calculated from the temporal distribution of the spray droplets.

A general trend of $D_{32}$ is that it increases with increasing the radial distance from the spray axis as shown in Fig. (6). This can be explained by the fact that the large droplets are affected by centrifugal force greater than that for smaller droplets. The centrifugal force makes larger droplets move radially far from the spray axis. This is also valid for the spray of diesel fuel and kerosene, Figures (7) and (8). Figure (9) shows the variation of both local SMD on the spray centerline and average SMD along the radial direction with the axial distance down the nozzle plane for water spray. Both local and average SMD decreases when moving axially far from the nozzle plane indicating that the larger droplets are under represented in the near field of the nozzle as their deceleration is considerably smaller than that for the smaller droplets. This is also valid for diesel fuel spray as shown in Fig. (10). Figure (11) shows the same relation of average SMD versus axial distance for kerosene spray at different pressure differentials One can observe that the above phenomena mentioned for water and diesel fuel is nearly reversed for kerosene specially at higher pressures. This different behavior for kerosene spray may be explained as kerosene has the smallest droplet mean diameter as well as it has relatively high volatility. Thus, these small volatile droplets have small life time and can be evaporated while traveling through the ambient air. As the distance traveled increases, the probability of evaporation of more small droplets increases and. therefore, the droplet mean diameter increases. Also, as expected, the higher the pressure differential across the nozzle, the finer is the spray.

### *4-3: Axial Mean Velocity*

In general, it is noticed that the axial mean velocity has its greatest value on the spray axis and decreases as the radial distance from the axis increases. Figure (12) reflects this fact for water spray at different pressure differentials and different axial positions. This result agrees with the results of many authors who used the same and different measuring techniques, e.g., [4] and [7]. This may be explained in view of the presence of larger droplets at the spray edges which have larger centrifugal force and smaller axial force, i.e., smaller axial velocity. Referring to Fig. (12), it can be noticed that the axial mean velocity decreases as the axial distance from the nozzle increases. As the atomization proceeds far from the nozzle exit, and the surface area of spray increases, the kinetic energy of the liquid is gradually dissipated to overcome frictional losses to the surrounding gas. Also, one can conclude that the axial mean velocity increases as the pressure differential across the nozzle increases. This expected result is due to increasing the kinetic energy converted from the pressure energy.

Comparison between the average axial mean velocity, along radial direction, for diesel fuel, water, and kerosene sprays is shown in Fig. (13). It shows that the diesel fuel has an axial radially averaged mean velocity greater than that for water along the studied axial distance. At distances close to the nozzle, kerosene has the largest axial mean velocity. Moving axially far from the nozzle plane, the velocity of kerosene has an intermediate value between water and diesel fuel, and at considerable distance it has the lowest values. This may be due to kerosene spray has the smallest droplets and, therefore, their inertia force is so small such that they can retarded faster as the droplets travel axially downward.

### *4-4. Liquid Volume Flux*

Liquid local volume flux on the axis of the diesel fuel spray is plotted versus the axial distance from the nozzle plane as shown in Fig. (14). It shows that the local volume flux on spray axis decreases as the axial distance from the nozzle plane increases. Also, Fig (15) shows the liquid volume flux on the spray axis of both water and kerosene versus axial distance. It is noticed that water yields the same result mentioned above for diesel fuel, but kerosene is different, i.e., the liquid volume flux increases as axial distance increases This may be due to kerosene has different relation between droplet mean diameter and axial distance from water and diesel fuel as mentioned above, i.e., the droplet mean diameter increases as the spray moves axially far from the nozzle plane.

Referring to Fig. (14), it is shown that, for diesel fuel spray, the liquid volume flux decreases as the pressure differential across the nozzle increases. Also, Fig. (16) shows a direct relation between liquid volume flux and pressure differential across the atomizer on the spray axis for both water and kerosene sprays indicating the same reverse dependence of liquid volume flux on the pressure differential, mentioned above for diesel fuel.

*4-5: Droplets Number Density*

Figure (17) shows the local number density along the spray axis and the average number density along radial direction versus the axial distance from the nozzle plane for diesel fuel spray. Power regression for the two plots are nearly identical. It is noticed that the droplet number density increases as the axial distance from the nozzle plane increases.

## 5- CONCLUSIONS

In the present study, it is aimed to examine the characteristics of a spray produced by a pressure swirl atomizer including the effect of the type of liquid atomized, pressure differential across the atomizer, on the spray characteristics at different spatial locations through the spray cone using the phase Doppler particle analyzer technique. The conclusions which were drawn from the present study can be summarized to the following points:

(1) P/DPA system is very useful and interesting device for measurements in the field of particle technology, as it is able to have the droplets count in different size classes, separately, and extract the temporal distribution from which the characteristic parameters can be evaluated. Also, measuring the droplet size and velocity simultaneously added the advantage that the temporal distribution can be converted to spatial distribution which is very useful in many applications. It is also useful for comparing its results with those from the other techniques that measure the spatial distributions only.

(2) At considerable distance from the nozzle plane, the droplet mean diameter, described by Sauter mean diameter, increases as the radial distance from the spray axis increases. The droplet axial mean velocity decreases as the radial distance increases.

(3) Increasing the axial distance, from the nozzle plane, makes droplet mean diameter decreases for both water and diesel fuel sprays but increases for kerosene spray. Also, the liquid volume flux for kerosene spray increases moving axially far from the nozzle plane, differing from that for both water and diesel fuel which decreases.

The droplet axial mean velocity decreases as the axial distance from the nozzle plane increases for all studied liquids.

(4) When the pressure differential across the nozzle increases, the droplet mean diameter and the liquid volume flux decrease, and the axial mean velocity increases.

(5) For the three liquids, kerosene has the smallest value for the droplet mean diameter compared with the water and diesel oil under the same conditions. In most of cases, water has the largest values of droplet mean diameters. Sometimes, diesel fuel competes with the water having larger droplet size.

## Nomenclature :

| | |
|---|---|
| D | Droplet Diameter |
| d | Atomizer Exit Orifice Diameter |
| n | Count of the Droplets |
| r | Radial Distance from Spray Axis |
| X | Axial Distance from the Nozzle Plane |
| k | Rosin-Rammler Exponent |
| $\Delta P$ | Pressure Differential across the Nozzle |
| $D_{32}$ | Sauter Mean Diameter, SMD |
| $D_{50}$ | Mass Median Diameter, MMD |

### Subscripts

| | |
|---|---|
| i | Droplet Size Class |

### Abbreviations

| | |
|---|---|
| MMD | Mass Median Diameter |
| SMD | Sauter Mean Diameter |
| P/DPA | Phase Doppler Particle Analyzer |

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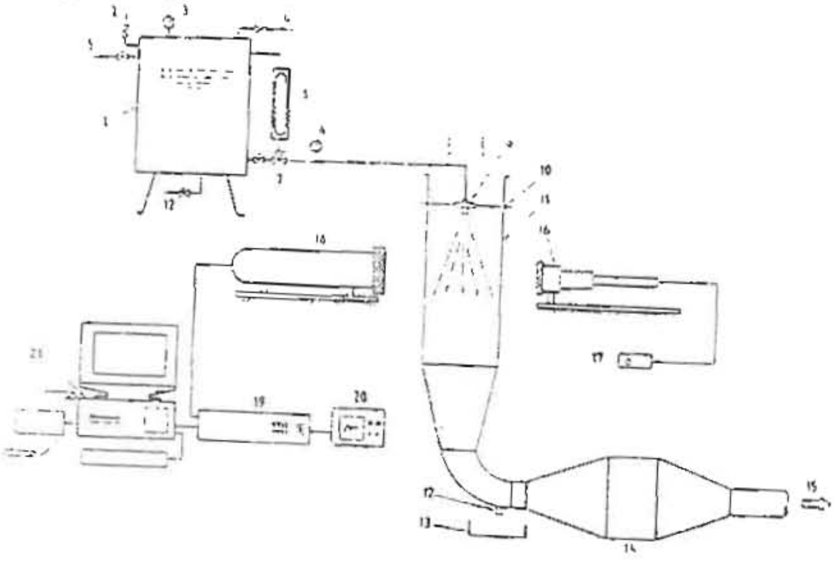


(1) Pressure vessel
(2) Vent
(3) Air press. gauge
(4) Compressed air inlet
(5) Liquid inlet
(6) Injection press. gauge
(7) Triple valve
(8) Metering burette
(9) Injection nozzle
(10) Traversing system
(11) Transparent test section
(12) Drain
(13) Drain tank
(14) Exhauster
(15) Exhaust to outside
(16) Laser beams transmitter
(17) Exciting power supply
(18) Receiver
(19) P/DPA signal processor
(20) Oscilloscope
(21) Computer

Fig ( 1 ) *Schematic Of The Experimental Set-Up*

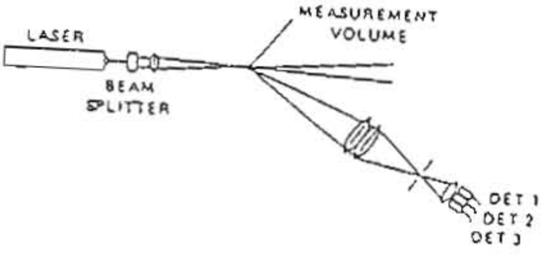


Fig ( 2 ) *Schematic Of The Optical System Used With LDV and P/DPA*

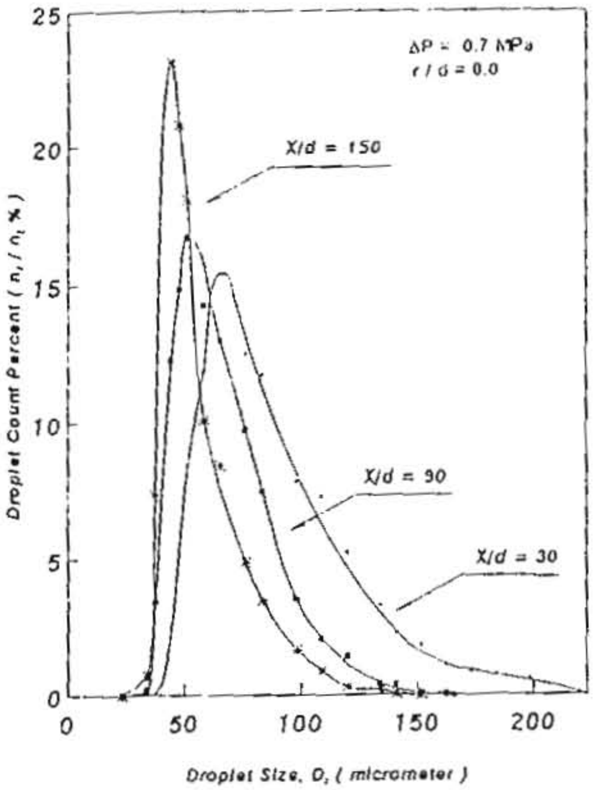


Fig. (3) Droplet size frequency curves for water spray at different axial locations

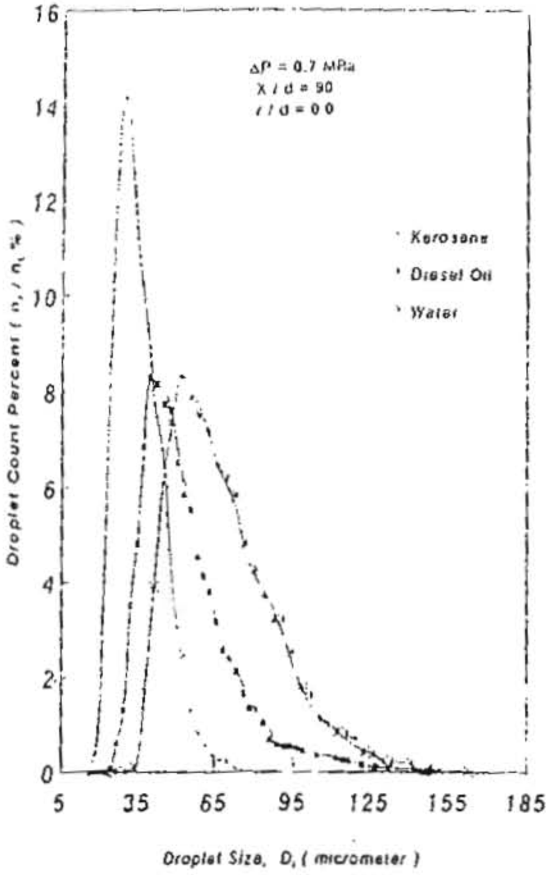


Fig. (4) Droplet size frequency curves for different liquids

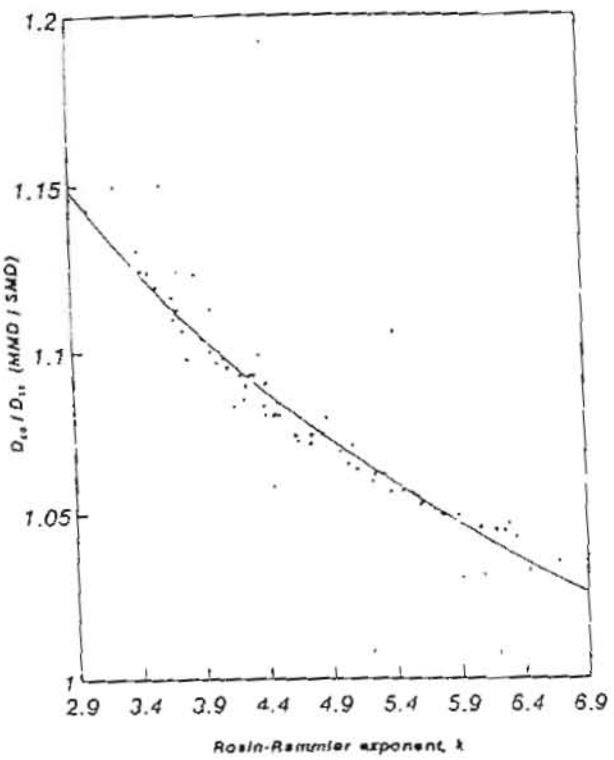


*Fig. (5)* $D_{50} / D_{32}$ ratio versus Rosin-Rammler exponent

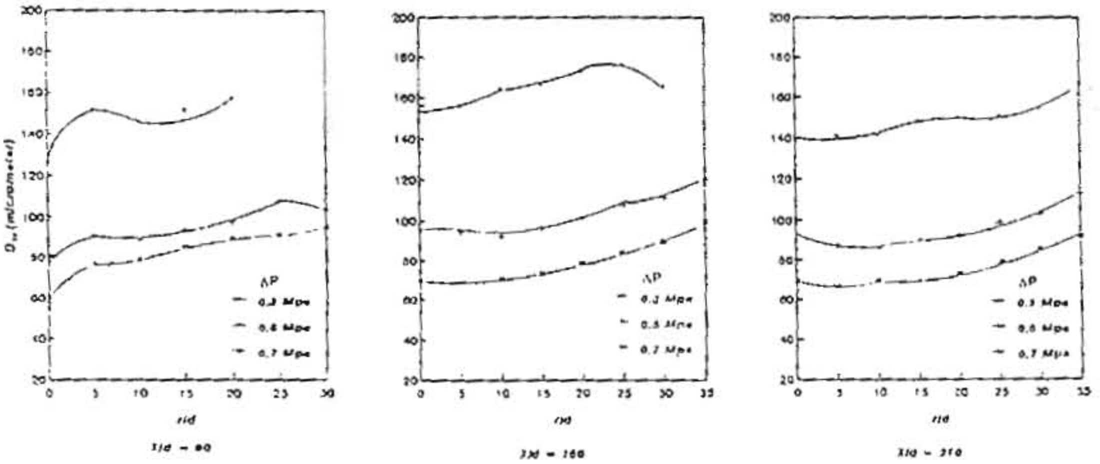
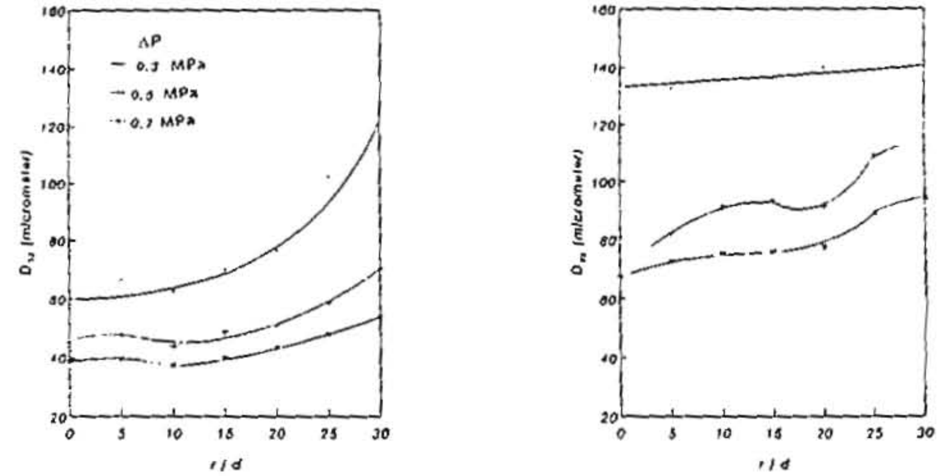


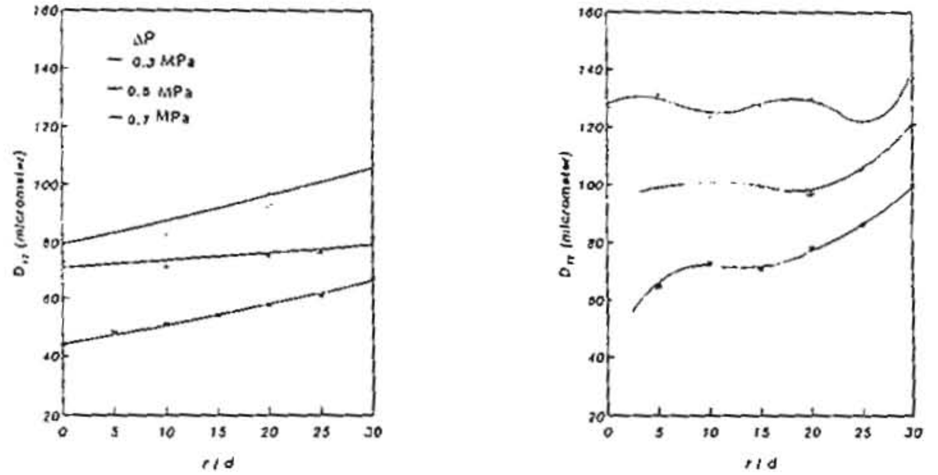
*Fig. (6)* Radial distribution of Sauter mean diameter for water spray at different axial positions



Kerosene

Diesel Fuel

Fig. (7) Radial distribution of Sauter mean diameter for both kerosene and diesel fuel at X/d = 90



Kerosene

Diesel Fuel

Fig. (8) Radial distribution of Sauter mean diameter for both kerosene and diesel fuel at X/d = 150

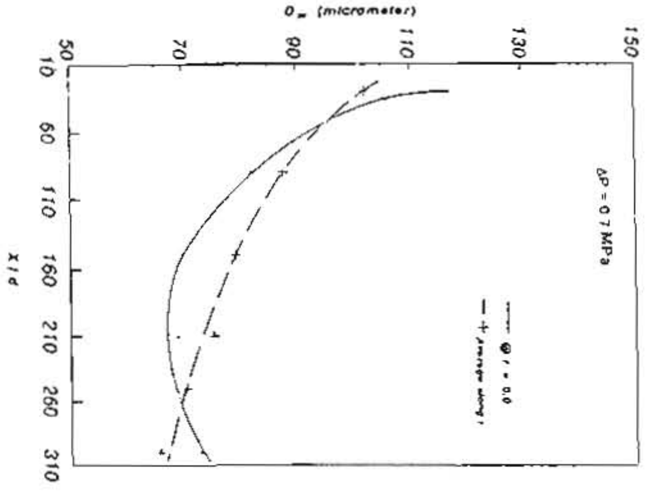


Fig. (9) Axial distribution of Sauter mean diameter for water spray

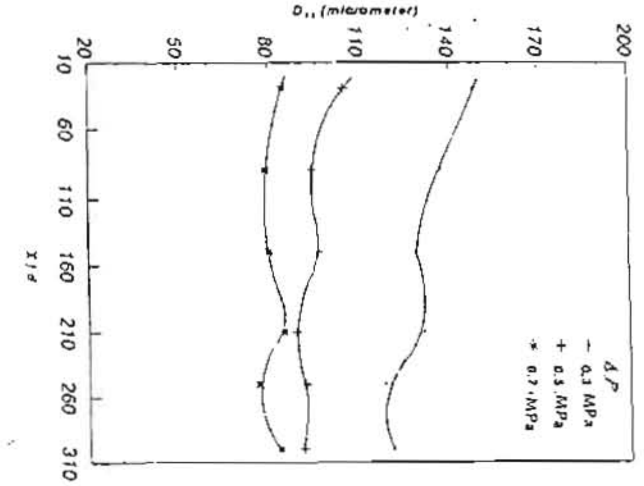


Fig. (10) Average Sauter mean diameter along radial direction versus axial distance for diesel fuel spray

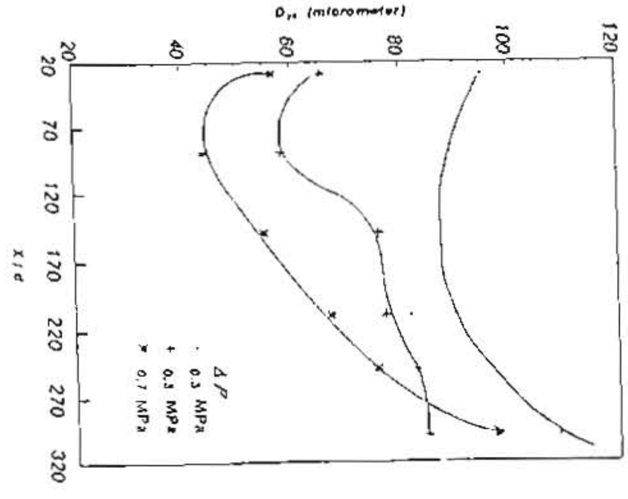


Fig. (11) Average Sauter mean diameter along radial direction versus the axial distance for kerosene spray

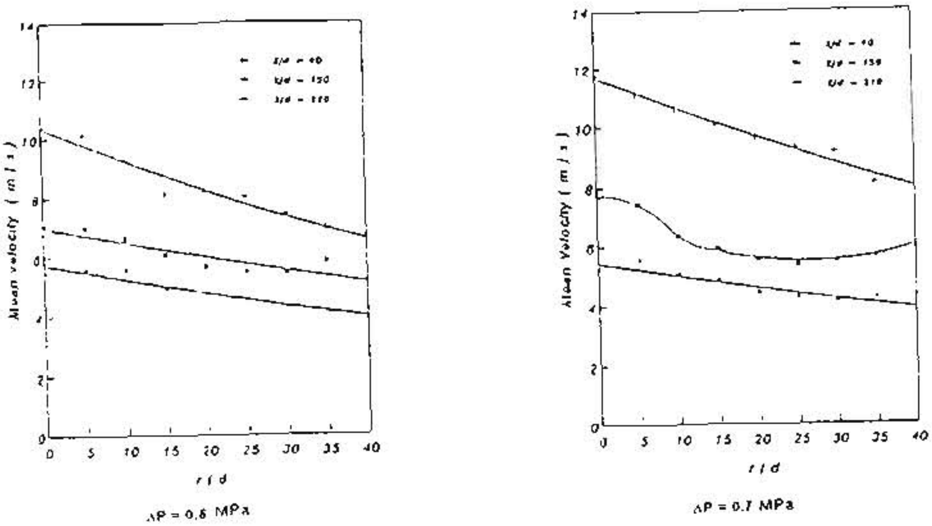


*Fig. (12)* *Radial distribution of droplet axial mean velocity for water spray at different pressure differential*

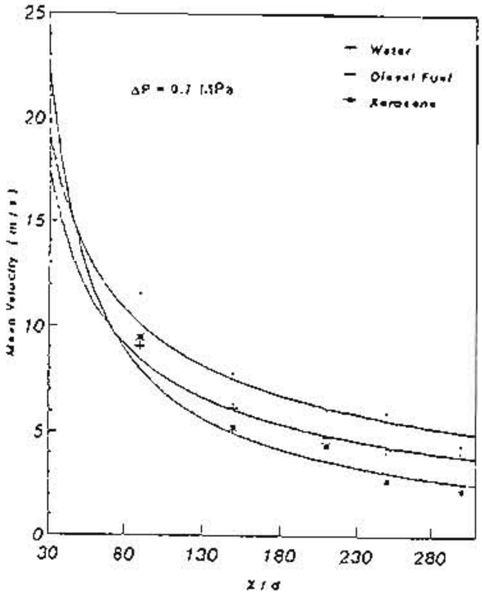


*Fig. (13)* *Average axial mean velocity versus axial distance for the different liquid sprays*

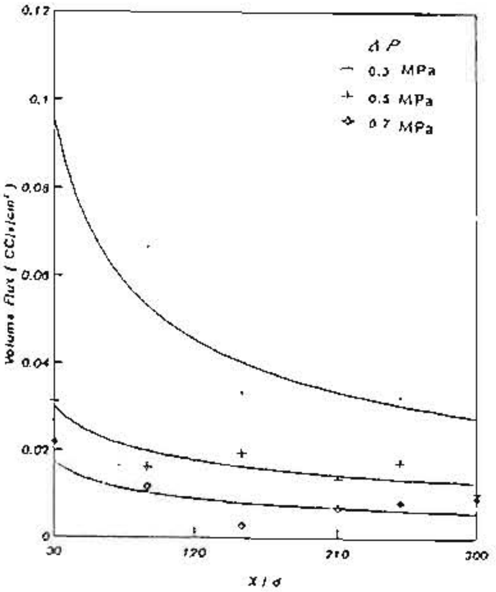


*Fig. (14)* *Axial distribution of liquid volume flux on axis diesel fuel spray*

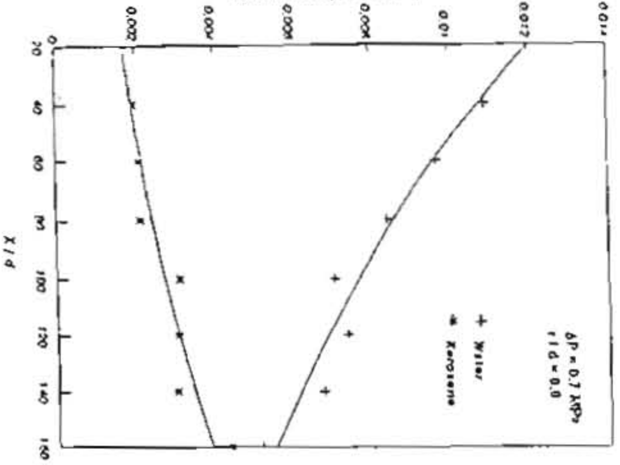


Fig. (15) Liquid volume flux versus the axial distance for water and kerosene sprays

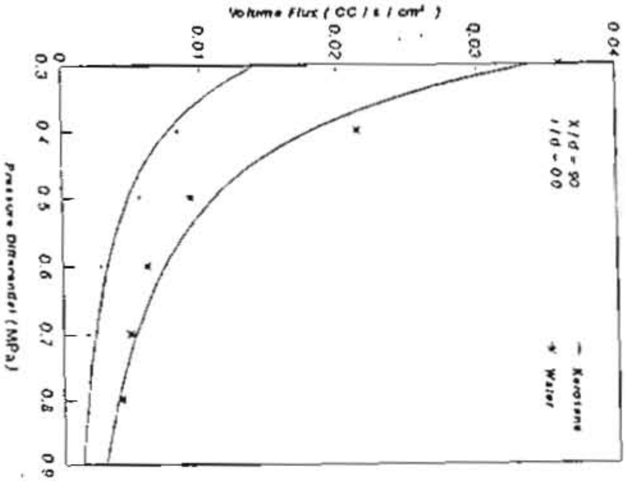


Fig. (16) Liquid volume flux versus the pressure differential across the nozzle for both water and kerosene spray

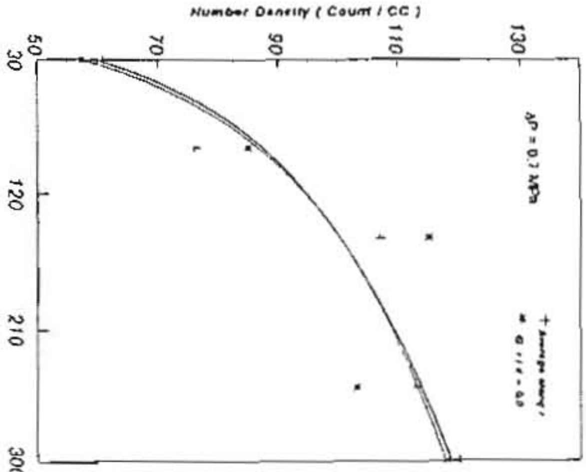


Fig. (17) Axial distribution of drops number density for diesel fuel spray