Velocity Measurements of Ink Drops Ejected from a Piezoelectric DOD Print Head—I. Technique Presentation

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Drop-on-Demand (DOD) print heads eject droplets through the air directly to a specified position on a media. Changes of shape and direction of the drops, which may also be followed by detached "satellite drops", usually occur during the motion toward the target. The quality of printing depends on the velocity fluctuations and on the existence of secondary drops. A Laser Doppler Velocimetry technique was applied to analyze the performance of ink jet printing heads close to real operating conditions. The system can provide a statistical description, which includes distributions and average parameters of the main and lateral velocities of drops. In addition, the technique can also detect the time between appearances of ejected drops that can provide information about of satellite drops existence, and the drops' transit time in the measurement volume, which can be used as a rough estimate of the drop size. By using these parameters, it is possible to develop experimental techniques enabling the analysis of ink jet printing performance. The results reported here show the existence of more than one drop between ejection pulses. In addition to the main velocity, the lateral velocity distribution was measured. Multiple peak distributions were obtained, in some cases, for the velocity in both directions. Low ejection frequency has a higher tendency to produce multiple peak distributions. Optimal operating parameters could be extracted using the proposed experimental technique.

Journal of Imaging Science and Technology 46: 171–181 (2002)

Introduction

Ink jet is a collective name for printing techniques that take small quantities of ink from a reservoir, convert them into drops, and transport the drops through air to the printed medium by appropriate application of physical forces. In some systems, referred to as continuous or pressurized ink jet, drops are formed at high rates even when there is no printing, and are selected and guided to the printed medium by electrostatic or magnetic forces. The other major classification is drop-on-demand (DOD), in which drops are formed only when required. The forces used to create and transport these drops may be mechanical, electrostatic or thermal. A review of the ink jet printing technology is given by Le.[1]

Ink jet printers are suitable for use in certain applications, such as computer output devices and word processors, marking of checks or packaged consumer products, printing on cloth and drapes and many other uses. Ink jet systems are particularly useful because of their low cost, high speed of printing, silent, non-impact operation, and ability to be electrically controlled by computers. Paper used in ink jet printers has color capability and requires no special after-treatment. Printing is possible on curved surfaces situated a few millimeters from the printing device.[2]

This research involves DOD printing head operation in which drops are squirted through a nozzle by changes in the volume of the ink chamber, caused by the deformation of a piezoelectric crystal attached to it. The deformation of the piezoelectric crystal generates a pressure wave that propagates toward the nozzle. This acoustic pressure wave overcomes the viscous pressure loss in a small nozzle and the surface tension force from the ink meniscus causes an ink drop to form at the nozzle. When the drop is formed, the pressure must be sufficient to expel the droplet toward a recording medium. The droplets are propelled toward the target by the remaining energy. Changes of shape and direction of the drops are observed during flight. Sometimes a secondary drop, called satellite, is detached from the main drop.

The particular print head checked here is used for the wide-format printing operation. The velocity measurements of ejected ink drops are important in order to find out the possible unwanted fluctuations on the target. The wide-format printing machine contains a wide rotating cylindrical barrel, to which the printing medium is attached by vacuum. A bridge on which print heads are fixed is located 1 to 2 mm. away from the medium and is capable of limited movements. A computer program is synchronized with the print heads to create the desired image on the medium.

Drops' velocity measurements in this field are not frequently reported in the literature. Gerhauser and coworkers[3] studied the behavior of DOD ink jet transducers. The experimental set up consisted of a long working distance microscope and a TV-camera with monitor. A strobe light or LED was used to provide the light for the camera.

Bogy and Talke[4] reported experimental results of the drop formation process using a rectangular voltage pulse. A light emitting diode, which was strobed at the

Original manuscript received June 5, 2000

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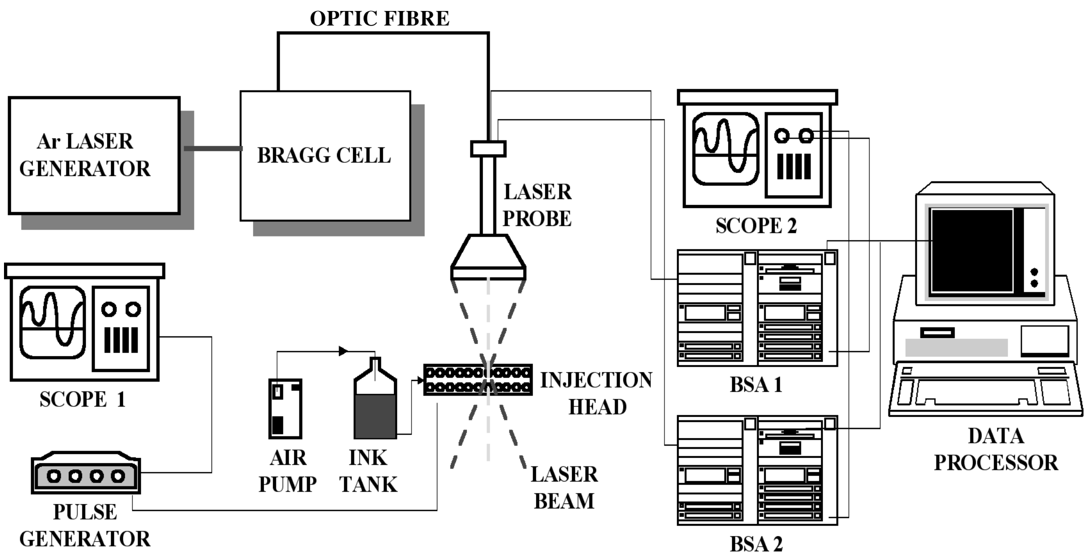

Figure 1. Schematic description of the experimental system.

frequency of drop ejection, was used. This freezes the drop and allows viewing on a TV monitor after suitable magnification. Typical changes in velocity detected by stroboscopic measurements are also shown in Howkin's[5] measurements.

Womac and co-workers[6] reported the performance of a pulsed-chamber with piezoelectric disk. A uniform-droplet generator was enhanced through the development of a digital pulse generator system. The effects of each pulse variable on droplet size and velocity were examined using a phase-Doppler particle analyzer (PDPA) and a photographic technique. The DPDA enables the measurement of droplet size and velocity. Droplet size increased with increased voltage, rise time, dwell time, fall time. Dwell time was statistically the most important variable affecting oil droplet size and velocity. Increased pulse voltage tends to increase droplet size and velocity because of increased impulse and momentum.

Droplet motion reported here was detected by means of an optical technique called Laser Doppler Velocimetry (LDV). In this method,[7] the flow field is illuminated by two laser beams. An interference pattern is formed at the two beams' intersection, made of parallel light fringes. When a particle passes through the intersection volume formed by the two coherent laser beams, it scatters light, which is collected by lenses and received by a photo-detector. The particle motion generates pulsating light intensity on the detector as the particle moves through the measurement volume. The scattered light signal fluctuates in intensity with a frequency equal to the velocity of the particle divided by the fringe spacing.

The LDV utilized to analyze the operation of printing heads is capable of measuring without interference to the flow and thus may be used in operation conditions. The velocity measurements are performed simultaneously in two directions. In addition, good statistics of a large number of drops in a short time are provided. Most of the past and even the present measurements of the drops' velocity use a stroboscopic light adjusted to the ejection frequency and a CCD camera. This method freezes an accumulation of many drops on a screen, measuring only a fraction of the velocity range, and is not capable of providing suitable information for all the velocity fluctuations existing in normal operation.

The digital printing industry is now one of the fastest growing industries, which develops products that affect our everyday lives. The use of computer controlled printing heads is the basis of the industry. There is a need to develop tools that will allow better information related to the motion of the ink drops in order to improve product quality, namely picture accuracy. Optimal operating parameters could be extracted using the proposed experimental technique.

The experimental system is described in the next section followed by the experimental procedure. Explanation of data reduction is given, followed by the analysis of the results, discussion and conclusions.

Experimental System

A schematic description of the experimental system is shown in Fig. 1. The experimental system is divided into three sub-systems.

System for Drop Formation

Drops were generated in a pusher type injection head.[5] Organic-based ink containing blue pigments, in this set of experiments, having a viscosity of 17.5 cp at 20°C and a density of 1.02 g/cm^3, was supplied to the injection head from the ink tank (Fig. 1). Drops were ejected by the contraction of Lead Zirconate Titanate (PZT) piezoelectric crystals operated by voltage signals. The piezoelectric print head contains 48 nozzles, 1 mm apart, in one row. The piezoelectric actuator is active in the longitudinal direction. The actuator is separated from the ink chamber by a diaphragm mounted to a silicone foot. The diaphragm prevents corrosion damage to the piezoelectric actuator. A restrictor partitions the ink in the ink chambers of each nozzle. When voltage is applied to the piezoelectric actuator, the PZT contracts, the diaphragm withdraws, drawing ink from the restrictor into the ink chamber, and the meniscus retracts. When the voltage is removed, the PZT expands, the diaphragm is pushed into the chamber and ink is driven out of the orifice and restrictor. Each nozzle has a diameter of 50 µm. A nozzle of this size ejects drops of 25 to 50 µm in diameter.

The pulse generator controls the frequency from 1 to 18 kHz, the voltage amplitude from 10 to 50 V, the pulse width from 7 to 30 μsec and the rise time from 2 to 10 μsec (Fig. 1). Oscilloscope 1 by LeCroy viewed the signal. A heating device was installed in order to maintain the temperature of the piezoelectric crystals of the injection head at 30°C. An on-off switch controlled each nozzle in the printing head. An air pump was used to fill the injection head before each experiment. During the experiment itself, the air pump was not used. The ink flows to the injection head by gravity. The whole drop generation system was placed in a sealed box in order to avoid possible movements of the drops due to air currents in the room.

Drop Detection System-LDV Measurement

Ink drop velocity was measured using the Laser Doppler Velocimeter described below: A one watt argon ion laser made by Coherent (California, USA) was used for the measurements. The laser was directed to a transmitter unit produced by Dantec (Skovlunde, Denmark). In this unit, a Bragg cell was activated. Two components of the laser beam, with wavelengths of 514.5 nm and 488 nm, were separated. Each wavelength was used for detection of drop velocities in one direction. Each monochromatic beam was split into two parts and a 40 MHz frequency shift, added to one of the beams in each wavelength. The frequency difference between the two beams of the same color allows the ability to distinguish between flow directions. The distance on the probe front lens, between the two beams of the same wavelength was 38 mm and was determined from the internal structure of the probe. The half angle between the two beams of the same wavelength, θ, was 9.65°.

The four beams were directed via optic fibers to a probe. The probe was located above the ink jets in order to bring the measurement volume to the path of a single jet. The two-beam pairs were perpendicular to each other. The probe was located in a way that one pair, λ = 488 nm, measured the velocity in the ejection direction, and the second, λ = 514.5 nm measured the side velocity perpendicular to the main component of the velocity vector.

A lens, with a focal length of 113 mm, which focuses the parallel beams to a point in space, was fitted on the probe. The probe was assembled in a special holder that enabled 90° rotation in the x-y plane. The 90° rotation enabled detection in each direction of measurement with any pair of laser beams. The probe holder was positioned on *x-y-z* table. This table allowed accurate movement in three directions and enabled the measurement volume to the exact measurement location, in an accuracy range of a few microns. The table was positioned on a heavy metal beam in order to reduce vibrations. The beam was placed on 20 soft tennis balls sitting on cork rings.

At the intersection volume of the two beams, fringes were created and used for the velocity measurement.[8,9] The volume created from the crossing of the two beams is the measurement volume. The distance between the two fringes in the measurement volume was 1.55 μm and 1.345 μm, for the two wavelengths. The dimensions of the measurement volume were 34 μm, 34.5 μm, perpendicular to the beams and 202 μm in the beam direction. The back-scattered light was collected by the lenses in the probe and was directed to a photo-multiplier tube connected via optic fibers. The collected light was separated into two different signals, using filters of two wavelengths. Each of the signals was analyzed by a Burst Spectrum Analyzer (BSA in Fig. 1), a product of Dantec, using a Fast Fourier Transform (FFT) to determine the frequency of the collected light signal. The velocities were obtained, by multiplying this frequency by the fringes' spacing, a function of the laser beam wavelength and the angle between the beams. Two BSA devices were used (BSA1 and BSA2) for the two direction velocities. This gave two perpendicular components of the drop velocity vector.

Data Processing

"Burstware" computer program collected data of successive velocities in two directions, calculated the statistics of the flow and accumulated all the data on the PC. Time of drops' appearances and information on the transit time i.e., time of passage through the measurement volume were also collected. In addition, the software enabled matching between two velocity components that were detected from the same drop. The signals from the two BSAs were viewed on oscilloscope 2. "Mathematica" software was used in order to assist in data analysis.

Procedure

The ink tank was filled with organic based ink with blue pigments. The probe was located above the ink jets to bring the measurement volume to the path of a single jet. The drop generating an electrical signal was set to a pulse width of 18 μsec, amplitude of 37 to 38 V, frequency of 1 to 18 kHz and 90% of the maximum rise time within 5 μsec. The injection head ran for half an hour before turning off all the nozzles, except the one that was used for the specific measurement.

The probe was positioned using the x-y-z table so that the measurement could be taken at a distance of approximately 2 mm from the orifice plate in the path of the ink jet, or closer to the nozzle. The height and horizontal position of the measurement volume within the ink jet were adjusted as the position that returned data at a high rate and a mean side velocity close to zero. Due to the fast response of the LDV system and the BSAs. This procedure took only a few minutes each time before accepting measurements.

After clear stable signals were detected by the BSAs and by oscilloscope 2 (Fig. 1), the computer was set to collect the data of about 10,000 drops in each measurement. After measurements were carried out, the Probability Density Function (PDF) of velocities was presented on the computer screen. At the end of the experimental session, the pulse generator was turned off and the orifice plate was covered with adherent polyethylene.

The printing head was washed with acetone and dried to remove all ink traces at the end of each measurement session.

Data Reduction

Each experiment was analyzed to study the measured velocities, their distribution, and the time between drops' appearances. Particle size was also estimated. The calculations are described in this section. The same data analysis was performed for every ejection frequency (between 1-18 Khz) and number of working nozzles.

Main and Side Velocities

The measured velocities of data from 10,000 collected particles were presented in histograms. Since it was exceedingly difficult to adjust the laser beam to exactly the same direction as the ejection jet flow, the average side velocity was usually not equal to zero. The side velocity was therefore corrected to a mean value of zero, by subtracting the average value from the side velocities. The values of the main velocities were unchanged since the magnitude of this error is negligible. The mean velocities and standard deviation were calculated. The coincidence between the main and side velocities was measured from particles that were detected concurrently by the two BSAs (coincidence was accepted when a difference between detection times was less than 9 μsec).

Drop Scattering of the Main and Side Velocities on Target

For the case of a roll of paper moving against the print head, the drop scattering was calculated as follows:

The flight time of a drop from the nozzle tip to the target paper located at a distance S is:

$$t = \frac{S}{V_{main}} \tag{1}$$

where S = 2 mm, usually, and V_{main} is the velocity in the main direction.

The scattering distance in the direction of the roll of paper, (in mm) is:

$$SD_{main} = t \times V_{roll} \tag{2}$$

where V_{roll} is the velocity of the roll of paper (order of 1 m/sec).

The scattering distance (in mm) in the perpendicular direction of the roll of paper is:

$$SD_{side} = t \times V_{side} \tag{3}$$

where V_{side} is the velocity perpendicular to the ejection direction.

Average Velocities and Standard Deviation

For the velocity of 10,000 collected particles, an average velocity was calculated at every frequency. The average of a set of such measurements at the same conditions was calculated and referred to as the summarized average. Error estimation was defined as the deviation of the average values from the summarized average value. The same calculations were done for the standard deviation.

Time Between Appearances of Drops

The time at which each drop was detected in the measurement volume was recorded. By subtracting the times between successive drops, the Time Between Appearances (TBA) was obtained. TBA was calculated between all detected drops.

Estimation of Particle Size

During the measurement, the transit time of each drop in the measurement volume was recorded. The transit distance, (in μm), was calculated using Eq. 4.

$$TD = V_{main} \times TT \tag{4}$$

where TT is the recorded transit time.

Results and Discussion

The results for velocities, drops' scattering (SD), time between appearances (TBA) of drops, particle size, mean velocity and standard deviation of the velocities are presented in this section.

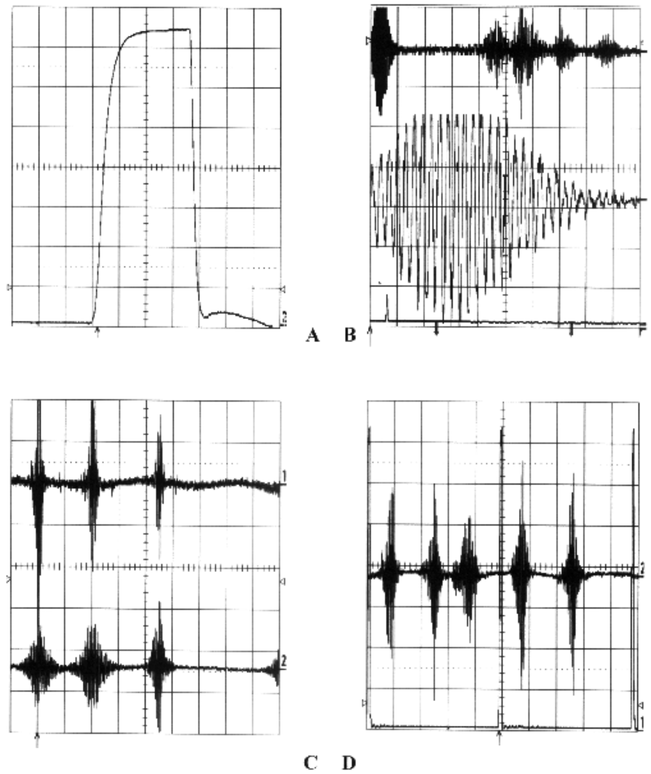

Figure 2. Oscilloscope readings for ejection in 1 kHz. (A) The generation signal; (B) Doppler signal and enlargement of the main drop signal; (C) Doppler signals for side (1) and main (2) direction; (D) Doppler signal for the main direction between generation pulses.

Figure 2 shows pictures of the oscilloscope screen during experiments with an injection frequency of 1 kHz. Figure 2A shows the injection signal. The horizontal axis is the time scale, 5 μsec per division. The vertical axis represents the signal voltage, which is 5 V per division. A product of the BSA device, a typical filtered Doppler signal, appeared on the oscilloscope as shown in Fig. 2B. This figure presents successive Doppler signals and an enlargement of the main velocity, the left signal. The frequency of the signal is obtained by FFT and the velocity is calculated as explained in section 3 by multiplying the frequency by the distance between fringes. An example of the FFT calculation (calculated by the oscilloscope) is shown in the figure by the lower line. For the enlarged signal, the frequency was 3.12 MHz, and the distance between fringes for this channel is 1.345 μm. This signal, therefore, corresponds to a velocity of 4.2 m/sec.

Figure 2C shows signals from both BSAs collected at the same time. The upper line shows the signals of the side velocity, and the lower line is the main velocity. It is clear that pairs of signals were generated by particles passing the measurement volume at the same time.

In most cases, more than one Doppler signal is observed between two injection pulses as seen in Fig. 2D. In this figure, three drop-generation pulses of 1 kHz are presented. Between the pulses, the centerline shows the Doppler signals with time intervals smaller than 1m/sec, which is the corresponding time for 1 kHz. It can be assumed that a few drops were created from the nozzle. This is usually referred to as satellite drops that are usu-

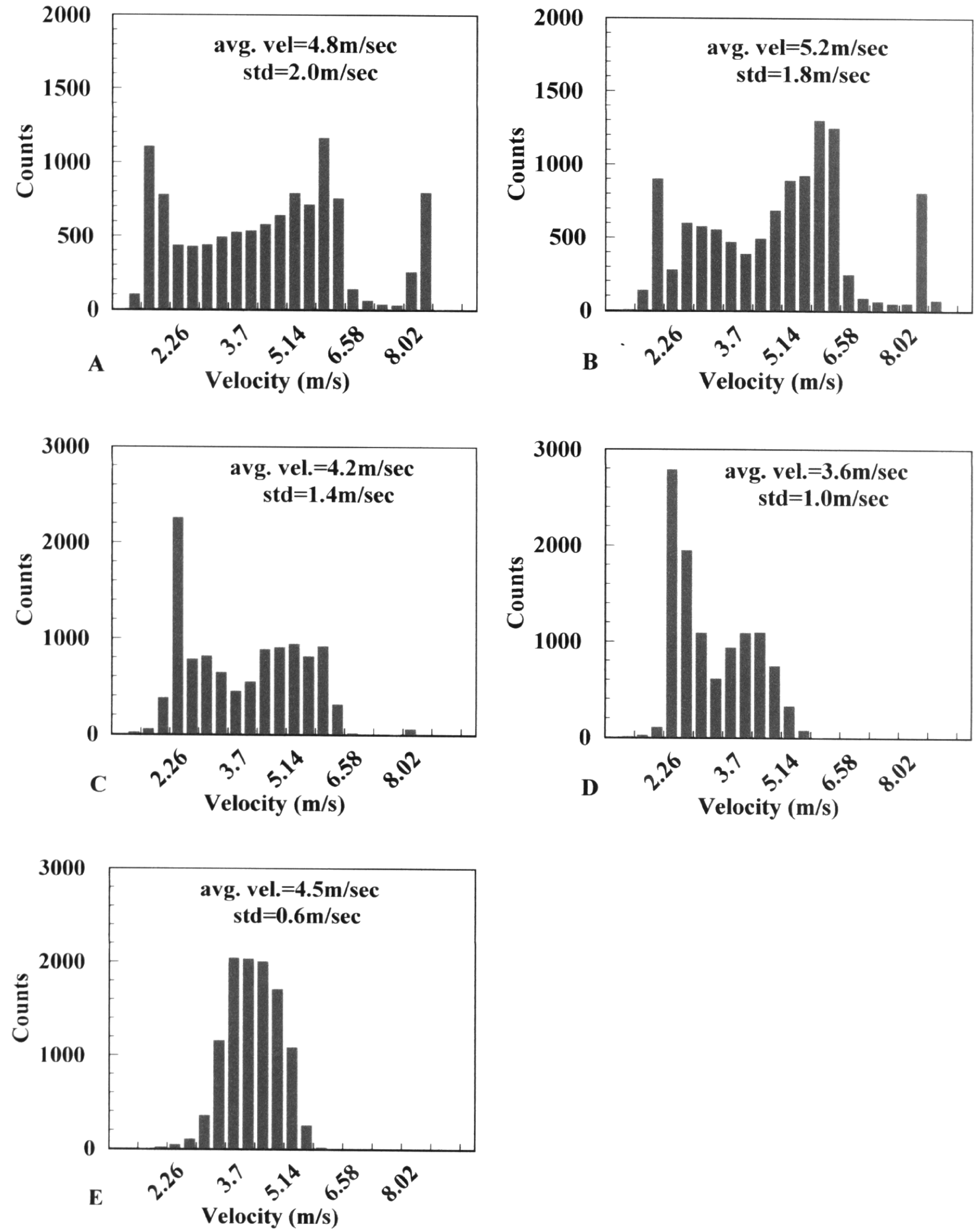

Figure 3. Main velocity of drops, at various generation frequencies. (A) 1 kHz; (B) 2 kHz; (C) 3 kHz; (D) 4 kHz; (E) 5 kHz.

ally considered to be much smaller than the main drop. It can be seen that multiple drops per generation signal are a common phenomena and that the drops are not so different in size, judging by the amplitude of the signals. It is desirable to find conditions that will reduce this phenomenon. An attention was made to secondary drops as a function of the velocity, ejection frequency, number of working nozzles and working time of the injection head. This will be discussed later in this section.

Main and Side Velocity

Figures 3 and 4 show PDF of the main and side velocities measured at injection frequencies of 1 to 5 kHz. As shown in Fig. 3, more than one maximum drop count in the velocity was detected for the main direction at some frequencies. For 5 kHz, multiple peaks no longer exist in this set. This type of result was observed in many of the experiments. A situation where more than one velocity peak exists was observed in PDF curves for the side velocity as well.

Main and lateral velocities were measured with one, two or three nozzles, working in parallel. No influence was found on the performance of a single nozzle as a function of the operation of one or two of its neighboring nozzles.

The maximum average velocity in this set of experiments was 7.9 m/sec and the minimum was 1.8 m/sec. This is lower than the velocities reported by Howkins

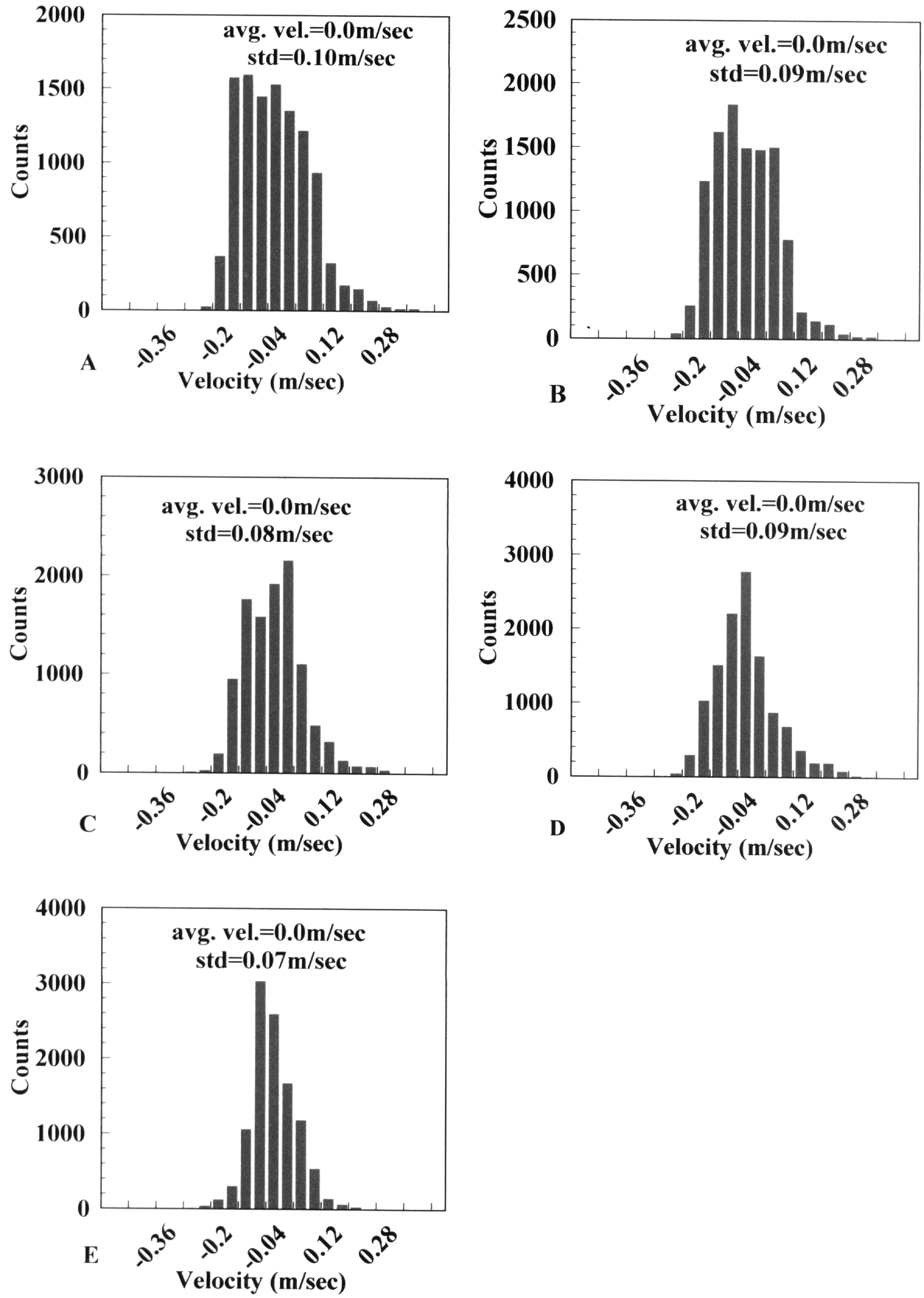

Figure 4. Side velocity of drops, for three adjacent working nozzles at various generation frequencies. (A) 1 kHz; (B) 2 kHz; (C) 3 kHz; (D) 4 kHz; (E) 5 kHz.

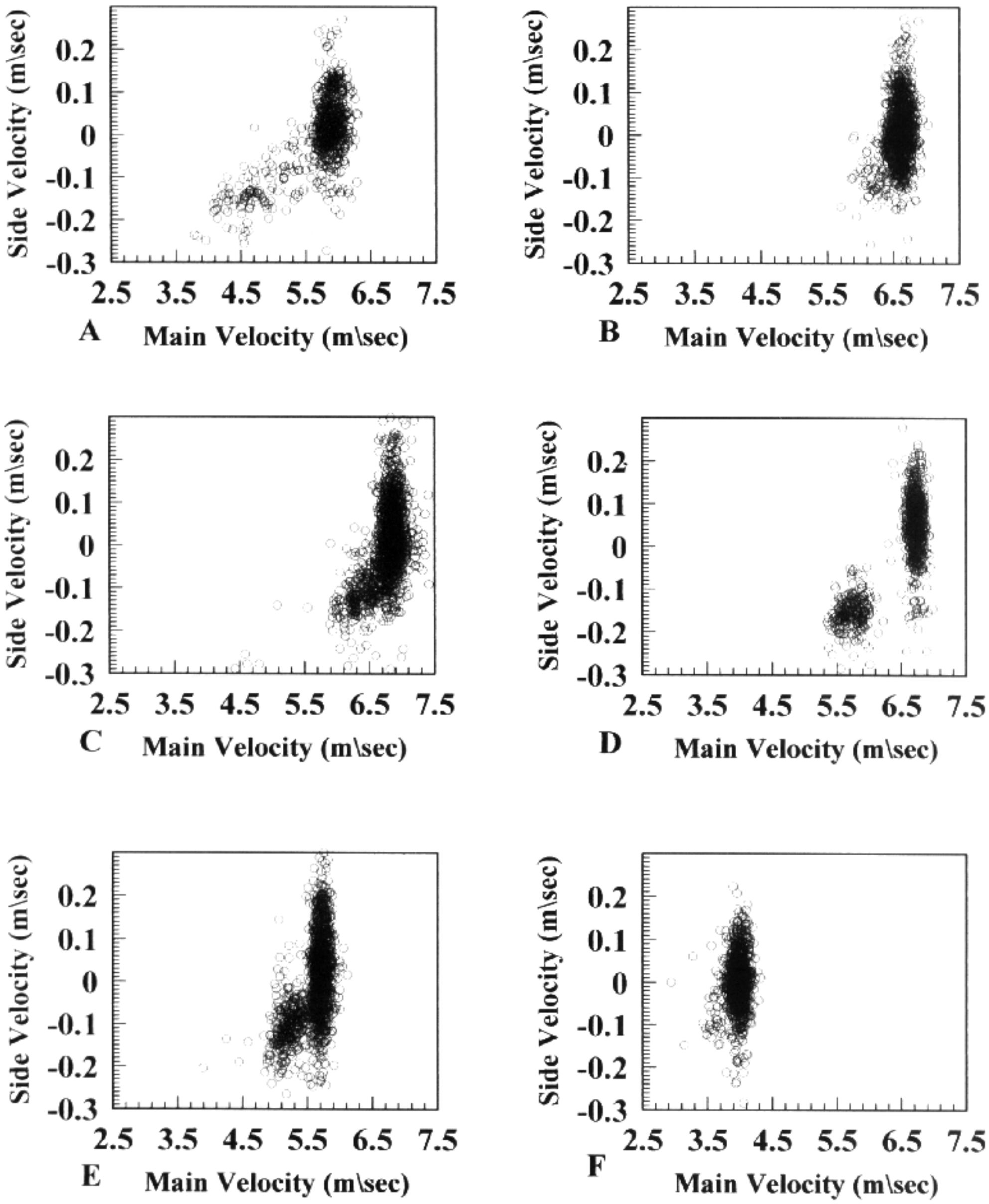

Figure 5. Relation between main and side velocity in various frequencies. (A) 1 kHz; (B) 2 kHz; (C) 4 kHz; (D) 6 kHz; (E) 8 kHz. F-10 kHz.

(1993)[5] that used similar print head, but a stroboscopic measurement technique. This average velocity was also independent of the injection frequency. The standard deviation was observed to be smaller than 2 m/sec for most experiments. The standard deviation of the lateral velocities was much smaller, usually less than 0.1 m/s, as can be seen in Fig. 4.

The relation between the main and side velocities for a wide range of ejection frequencies is displayed in Fig. 5, which shows the side velocity versus the main velocity for all the drops that passed the measurement volume coincidently, as explained earlier. Similar pictures were commonly observed in other experiments including the ones with 1 or 3 nozzles in operation. It is clear that the patch drawn should represent a dense ellipse due to the large difference between the two velocity scales. The extra patches that appear in the figure are clusters of multiple peak velocities and large deviations from the average velocities, which are not desired in operation.

Drops Scattering on the Printing Roll Paper

Assuming that the roll of printing paper moves at a speed of 1m/sec, the scattering of drops in both directions was calculated according to Eqs. 2 and 3, and is presented in Fig. 6. Figures 6A and B are the main and side velocities, respectively. Figures 6C and 6D are the main and side SD values calculated based on the velocities in 6A and B.

The problematic consequences of the multiple velocity peaks are shown in Fig. 6. During printing, the paper moves with a constant speed. If more than one value of the main velocity exists during ejection, drops will spread on the paper in the same direction of the paper motion, over a distance that depends on the drop velocity. A spread in the direction perpendicular to the direction of the moving paper also occurs due to the side velocity distribution that also exists (Eq. 3). These values determine the resolution of the printing. The spread in the paper motion is much larger than the

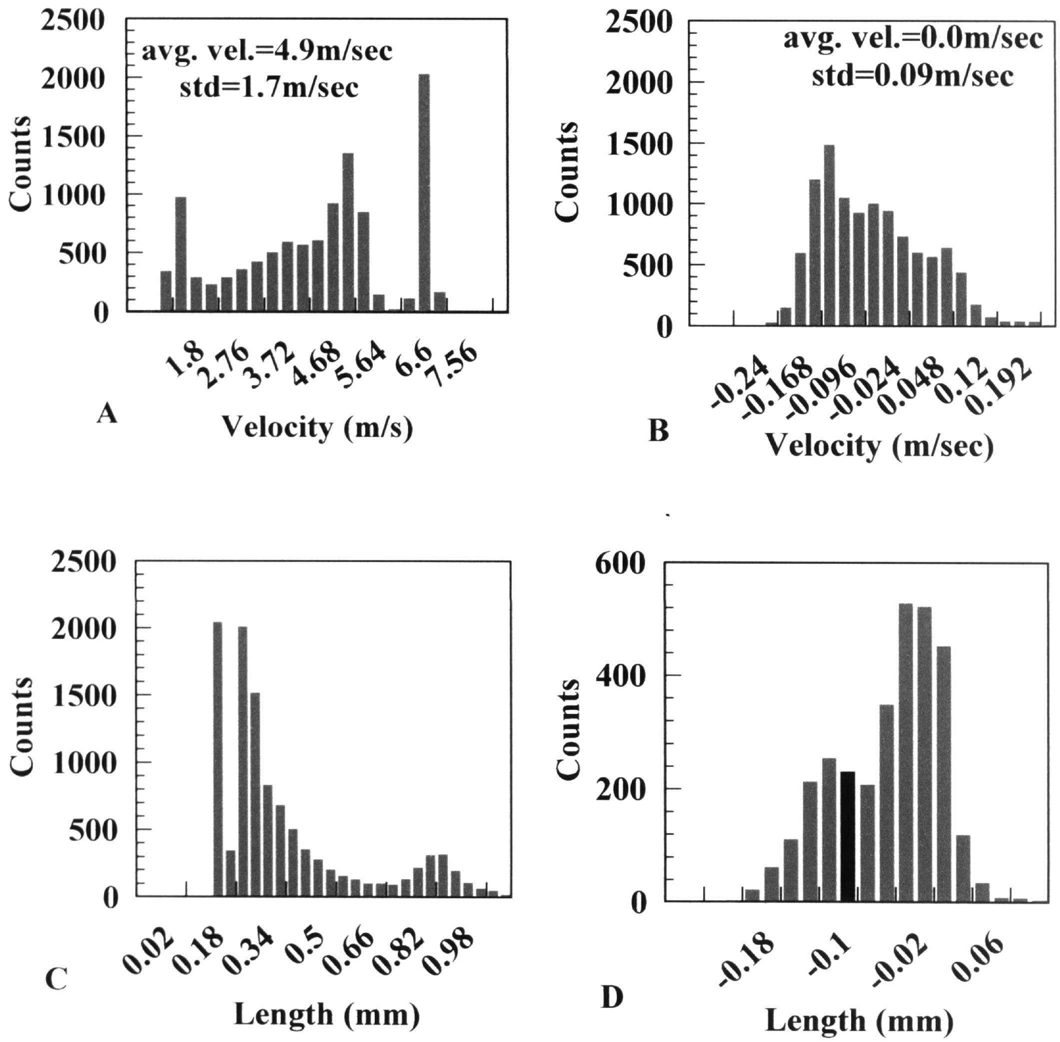

Figure 6. Scattering of drops in both directions 1 kHz Ejection. (A) Main Velocity Histogram; (B) Side velocity histogram; (C) Spread length histogram in the main direction; (D) Spread length histogram in the side direction.

spread in the lateral direction. Usually the spread is smaller than the results presented here, but this is a good example of the strength of this evaluation method. While the lateral spread is within the range of ±150 μm, the spread in the paper direction is of the order of ±400 μm, and will have intensity peaks, as shown in the figure, based on the different velocity maxima. The fastest drop will meet the paper after it moves a distance of about 0.3 mm from the time of the drop ejection, while the slowest drop will be shown on the paper after 1.1 mm.

Time Between Appearances (TBA)

An ideal drop ejection followed by a successive detection generates a single drop signal for each ejection pulse, namely no satellite drops exist and all drops are detected. The TBA, calculated as described earlier, is expected therefore to be exactly one over the injection frequency. Thus for an ejection at 1kHz the corresponding TBA is a period of 1 m/sec, for 2 kHz it is 0.5 m/sec etc. The TBA for all detected signals is supposed to show only the inverse value of the injection frequency. Since not all drops are detected by the LDV, a multiplicity of this time will be found. In cases where satellites appear or when there is a velocity distribution in the main direction, drops' detections will occur in times between the ejection frequency reciprocals.

The TBA for multi-peak velocity histogram measured in an experiment with a single working nozzle is shown in Fig. 7. Figure 7A presents a PDF of the velocity in the target direction, and Fig. 7B reveals the existence of TBA values different from those expected for the main velocity distribution in Fig. 7A at 5 kHz (TBA expected of 0.2 msec). This is a probability distribution function of the time between drops' appearance. It is clear that many drops appear at different intervals than the reciprocal of the ejection frequency and its multiplicity. To study this further, the TBA was calculated only among the signals that have velocities in limited ranges. For this purpose the results file was separated into three parts according to the measured velocity, based on the different peaks shown in Fig. 7A, and the TBA was calculated again for each part. This gave the partial TBA depicted in Fig. 7C-E. It is seen clearly in Fig. 7C and 7D that for the two low velocity ranges, around 2.5 m/sec and 4.5 m/sec, the TBA distribution is not clear enough. At higher velocities, around 7.5 m/sec, however, the TBA was observed mainly at periodic intervals of 0.2 m/sec as may be seen

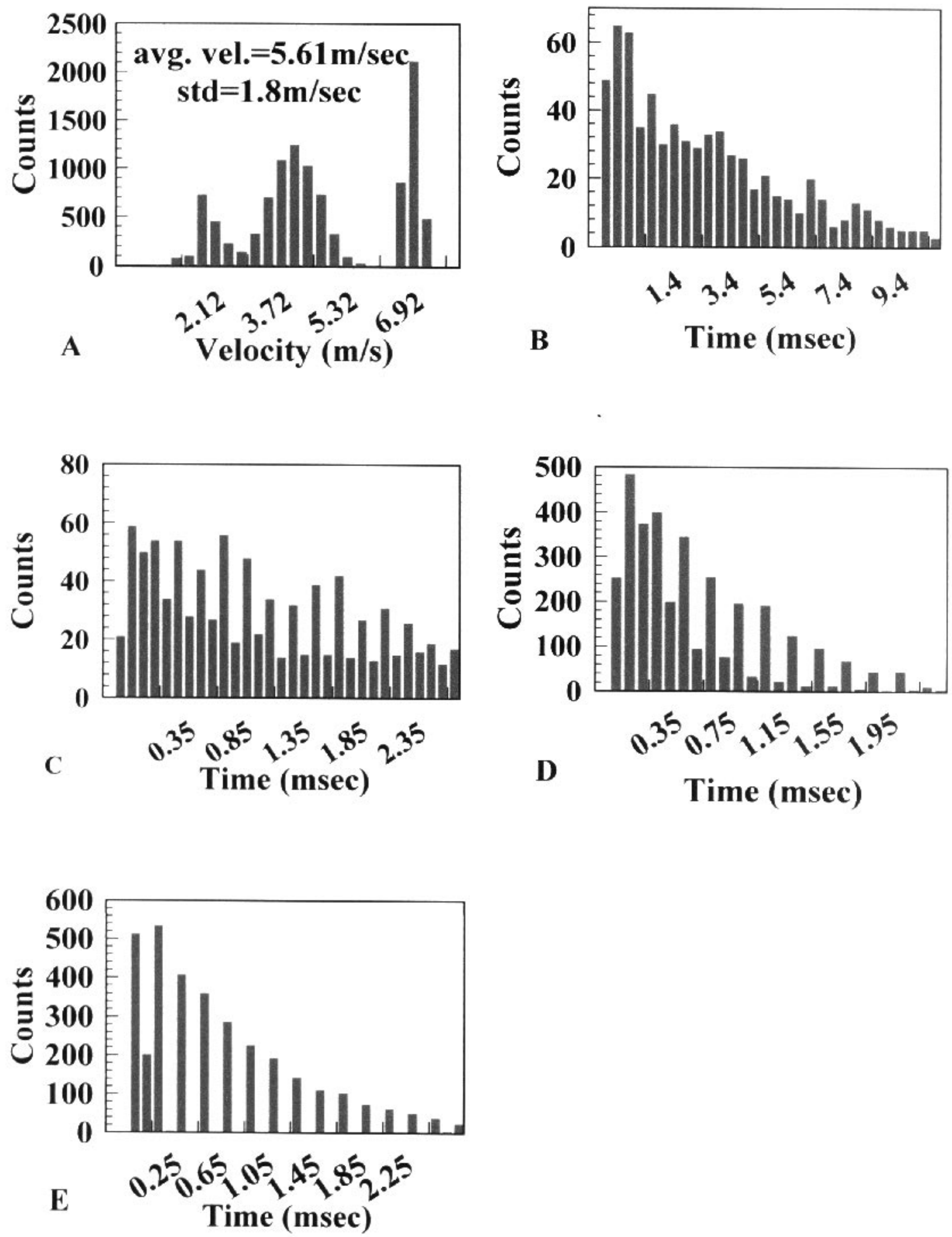

Figure 7. Time between appearances in 5 kHz ejection frequency. (A) Main velocity histogram; (B) TBA for all drops; (C) TBA for drops with velocity in range of 2.28 to 3.34 m/sec; (D) TBA for drops with velocity in range of 4.2-5.8 m/sec; (E) TBA for drops with velocity in range of 7.4 to 8.4 m/sec.

in Fig. 7E. This is another tool to predict the spread of the drops and the existence of extra, unwanted drops.

Estimation of Particle Size

A rough estimation of particle size can be obtained from Transit Distance (TD, Eq. 4) by subtracting the passage length along the measurement volume. Better techniques for estimation of drops' sizes exist, but they are out if the scope of this work. In order to get an accurate size estimation, it is necessary to know the exact path of the particle within the volume of measurement. This cannot be accomplished in practice. The maximum size of the measurement volume is 31 μm; by subtracting this, TD will give a lower value than expected when the particle is not centered in the measurement volume. A larger size will be obtained when the drops are too close to each other and the resolution of the system is not sufficient for proper separation between the particles

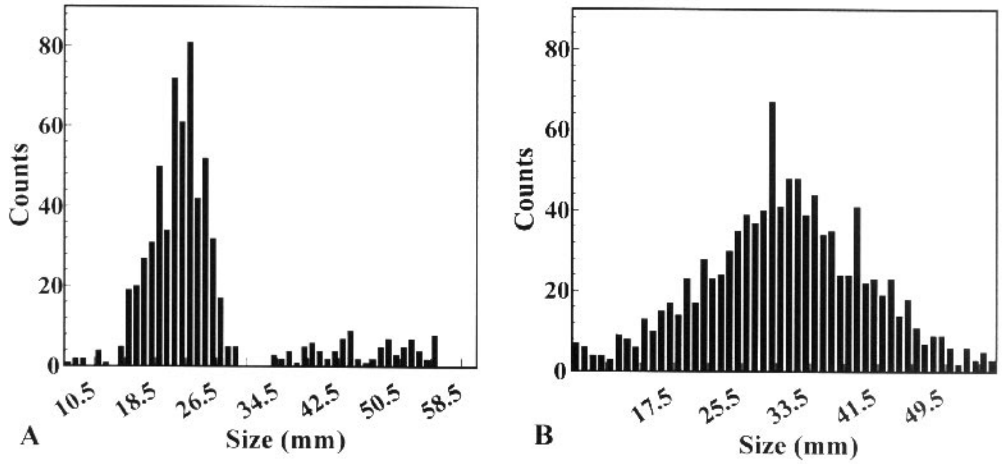

Figure 8. Transit distance (TD) of drops. (A) 1 kHz; (B) 10 kHz.

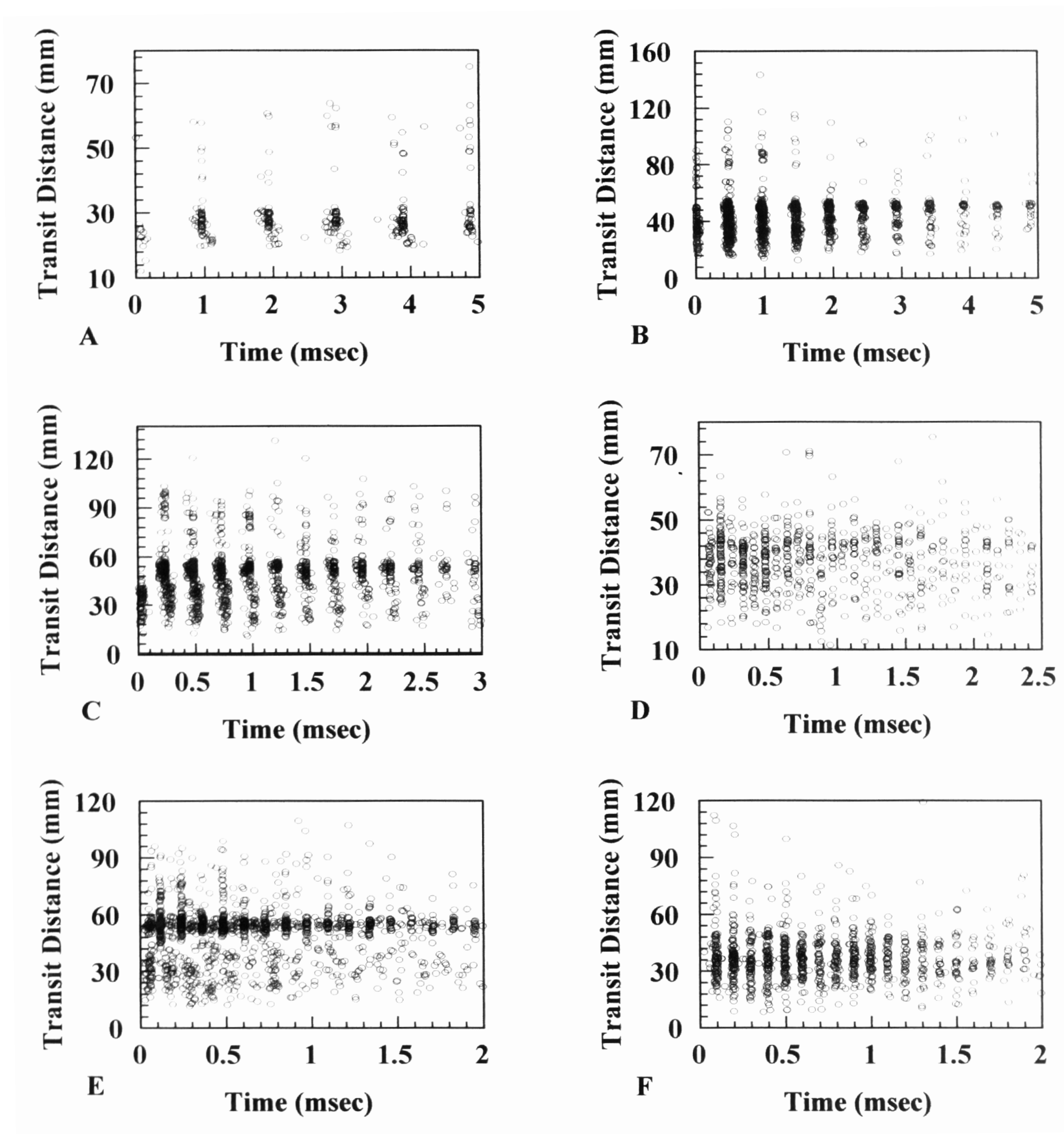

Figure 9. Transit distance (TD) of drops as a function of TBA. (A) 1 kHz; (B) 2 kHz; (C) 4 kHz; (D) 6 kHz; (E) 8 kHz; (F) 10 kHz.

in the measurement volume. Nevertheless, as said, the TD provides a rough estimation for particle size shown in Figs. 8 and 9.

Most of the size values calculated from the measurements were between 10 μm to 50 μm, where the most probable sizes are between 24 and 33 μm for the two different examples. The reported values for particle size are between 15 μm to 30 μm for satellite and main drops respectively, with no statistical parameters. These values agree with the calculated rough size estimations.

Relation between TD and TBA was checked in Fig. 9. This was done in order to estimate a relation between drops' size and time of appearance, in order to identify satellite drops. It can be seen in the figure that the density of TBA data around the injection frequency is not a significant function of the TD values. This supports the conclusion that the TBA does not correlate to the size of drops. In Fig. 9D-E more satellite drops seems to appear at 6 kHz and at 8 kHz ejection. This cannot be related to the ejection frequency, but it can tell when a relatively large number of irregular drops coexist with regular ones.

Conclusions

The LDV utilized to analyze the operation of print heads is capable of measuring accurately the velocity of a large number of drops at a short time while yielding useful statistics of measured parameters. The technique may be used at operating conditions. The velocity in both directions and the corresponding standard deviation can be accurately detected to allow calculations of the drop scattering on the target. The technique can detect the existence of irregular drops' velocity distribution and the existence of satellite drops. A rough estimation for particle size is also provided.

It was found that more than one drop usually exists between ejection pulses. The number of drops varied up to four detected drops. In addition to the main velocity, a side velocity distribution was detected. Multiple peak distributions were obtained for the velocity in both directions. It was also found that drops produced at high velocities tend to produce less satellite drops. Operation of neighboring nozzles had no effect on the value of velocities, their standard deviation or amount of satellite drops.

References

1. H. P. Le, Progress and Trends in Ink Jet Printing, *J. Imaging Sci. Technol.* **42** (1) 49–62 (1998).
2. J. Heinzl and C. H. Hertz, Ink Jet Printing, *Advances in Electronics and Electron Physics* **65,** 91–171 (1985).
3. H. Gerhauser, J. H. Hirschmann, F. Lee, and F. E. Talke, The Effect of Pulse Shape on the Drop Volume and the Frequency Response of DOD Ink Jet Transducers, *SID Digest* **224,** 110–111 (1983).
4. D. B. Bogy and F. E. Talke, Experimental and Theoretical Study of Wave Propagation Phenomena in D.O.D Ink Jet Devices, *IBM J. of Res. Dev.* **28** (3), 314–321 (1984).
5. S. Howkins, Physical Limitations on High Performance Piezo-electric Pusher Technology, *SPIE* (*Color Hardcopy and Graphics Arts*), **1912,** 142–152 (1993).
6. A. R. Womac, J. R. Williford, B. J. Weber, K. T. Pearce, and D. L. Reichard, Influence of Pulse Signal Spike and Liquid Characteristics on Performance of Uniform Droplet Generation, *Trans-ASAE* **35** (1), 71–79 (1992).
7. M. J. Rudd, A New Theoretical Model for the Laser Dopplermeter, *J. Phys. E: Sci. Instrum.* **2,** 55–58 (1969).
8. L. E. Drain, *The Laser Doppler Technique*, John Wiley and Sons, Chichester, UK, 1980.
9. F. Durst, A. Melling and J. H. Whitelaw, *Principles and Practice of Laser Doppler Anemometry*, Academic Press, London, 1981.