DROPLET SIZE AND VELOCITY MEASUREMENTS

for Tav-Tech Ltd

(REPORT to Tav-Tech Ltd., ISRAEL)

by

Dr. Vitaly Ovcharenko

Prof. Yeshayahou Levy

Turbo and Jet Engine Laboratory

Faculty of Aerospace Engineering

Technion-Israel Institute of Technology, Haifa

JTL 002-07-2015

July 2015

DROPLET SIZE AND VELOCITY MEASUREMENTS

PDPA/LDV measurements

TSI, Incorporated the Phase Doppler Particle Analyzer/Laser Doppler Velocimeter (TSI PDPA/LDV) system is an optical technique to simultaneously measure the size and velocity particles. These particles can be droplets, bubbles or solid particles, as typically occur in sprays, liquid atomization, bubbly two-phase flows and multiphase flows.

PDPA systems are used in a wide variety of disciplines around the world. Following is just a few examples of areas where TSI PDPA systems have been used:

1. **Combustion research:** Measurement of fuel droplets.
2. **Aircraft icing research:** Measurement of water and ice drops and their affect on aircraft
3. **Ink-jet printer development:** Improve performance of ink-jet printers. Both size of drops and the trajectories of drops being fired are measured.
4. **Basic industrial sprays research:** PDPA is used to characterize various chemicals that are atomized (pesticides, petrochemicals, etc.).
5. **Spray drying:** Used in pharmaceutical and food applications.
6. **Characterization of Metered Dose Inhalers (MDI's):** Characterize the size and velocity of droplets produced by medical inhalers.
7. **Paint sprays:** Characterization of drop size distributions

A fiber based laser measurement TSI Inc. Phase Doppler Particle Analyzer/Laser Doppler Velocimeter (TSI PDPA/LDV) system was used for the measurements. It contains the following major components (shown on Figure 1):

- Laser light source - the system is integrated by Ar-laser (2017 model).
- Light separation optics - Fiberlight Multi-color Beam Separator generates the laser beams needed for two- or three-component PDPA systems and couples the laser light into the transmitting optics for delivery to the measuring volume.
- Light transmitting optics
- Light collecting optics - Fiberoptic Receivers have several unique features that make them ideal for particle size and velocity measurements. By utilizing a fiber bundle instead of individual fibers for light collection, the TSI Fiberoptic Receivers are easy to align and provide high optical efficiency. Integration of the calibration diode light back through the receiver provides an optimum phase calibration for ensuring the accuracy of particle size measurements.
- Photodetectors - Photodetector Module (PDM) system combines an enhanced scattered light separation unit with high performance photomultiplier tubes and initial signal conditioning electronics. The PDM is optimized for high dynamic range and is software controlled.
- Signal processing electronics - Flow and Size Analyzer (FSA) processors are the fastest, most accurate ever developed for PDPA applications. Utilizing a firmware based approach and two powerful digital processing techniques, FSA processors are optimized for different PDPA applications. Data transfer is done via the FireWire (IEEE 1394) standard interface
- External data input devices - A compact multi-channel interface that lets combine pressure, temperature or similar analog or digital data with the velocity measurements. For periodic or pulsatile flows, the device also may collect encoder or phase angle information for phase-locked data acquisition and analysis.
- Computer - Systems run on Windows based PC computer, through the FireWire communication interface.
- Software - FlowSizer Data Acquisition and Analysis Software is used for set-up, control and operation of PDPA systems.

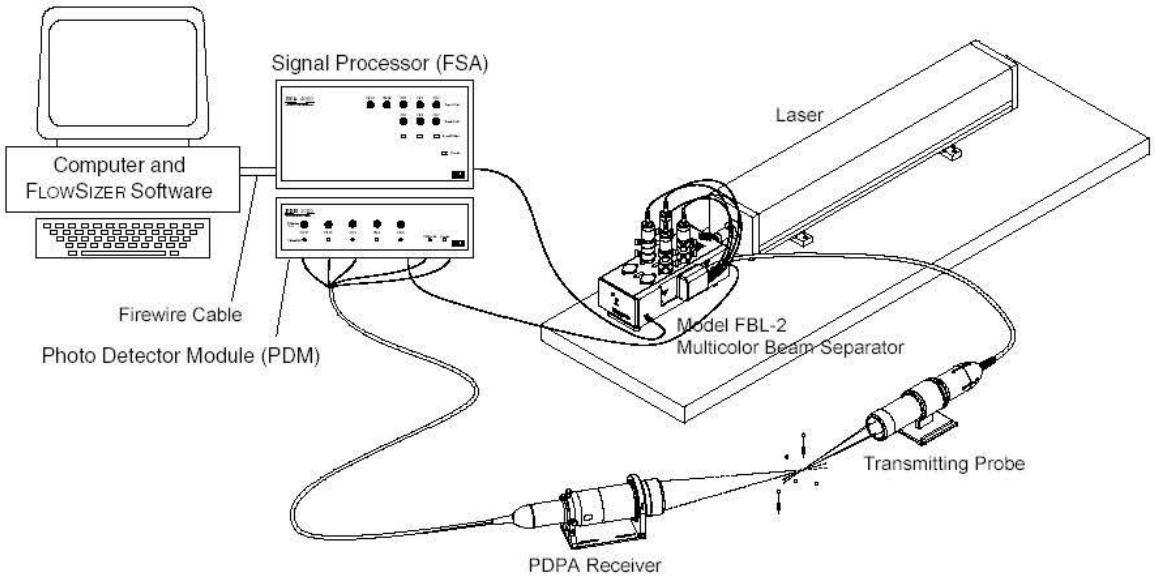


Figure 1 TSI PDPA/LDV system

Major measured parameters

Velocity Statistics provides the **mean** and the **root-mean-square (RMS)** values of velocity for each component. The **turbulence intensity** is the ratio of RMS to mean velocity expressed in percent. The system measures two components of velocity, vertical and horizontal. Its combination with X, Y, Z-traverse system yields a unique capability to execute measurements of radial and tangential component velocity of droplets in spray.

Velocity Mean (m/s): The average velocity value of all the velocities measured

$$\bar{V} = \frac{\sum_{i=1}^{n} V_i}{n}$$

V_i = Velocity for *i*-particle,

n = number of particles.

Velocity RMS (m/s): Standard deviation of the velocities measured

$$V_{RMS} = \sqrt{\frac{\sum_{i=1}^{n}\left(V_i - \bar{V}\right)^2}{n-1}}$$

The **diameter statistics** consist of various mean diameters, i.e., number mean D_{10}, surface mean D_{20}, volume mean D_{30}, Sauter mean D_{32} and D_{43}. The following general definition applies to all of the above mean diameters:

$$D_{mn} = \left(\frac{\Sigma D^m}{\Sigma D^n}\right)^{\frac{1}{m-n}}$$

Example: D_{32} (um) or the Sauter Mean Diameter (SMD):

$$D_{32} = \frac{\sum_{i=1}^{n} D_i^3}{\sum_{i=1}^{n} D_i^2}$$

Di = diameter of i-particle,

n = number of particles.

In Table 1 the particle diameter measurement range (in the Technion's systems), depending on lens focal lengths of transmitter and receiver units sand at different refraction index values, N, presented.

Table 1 Range of measured droplet diameter by PDPA system

Ar-laser, 514.5 nm		Water droplets, n = 1.332	
TR260-X10 Transmitter Lens focal length, mm	RV2070 Receiver Lens focal length, mm	Min. Diameter um	Max. Diameter um
500	500	0.8	350

Measurement results

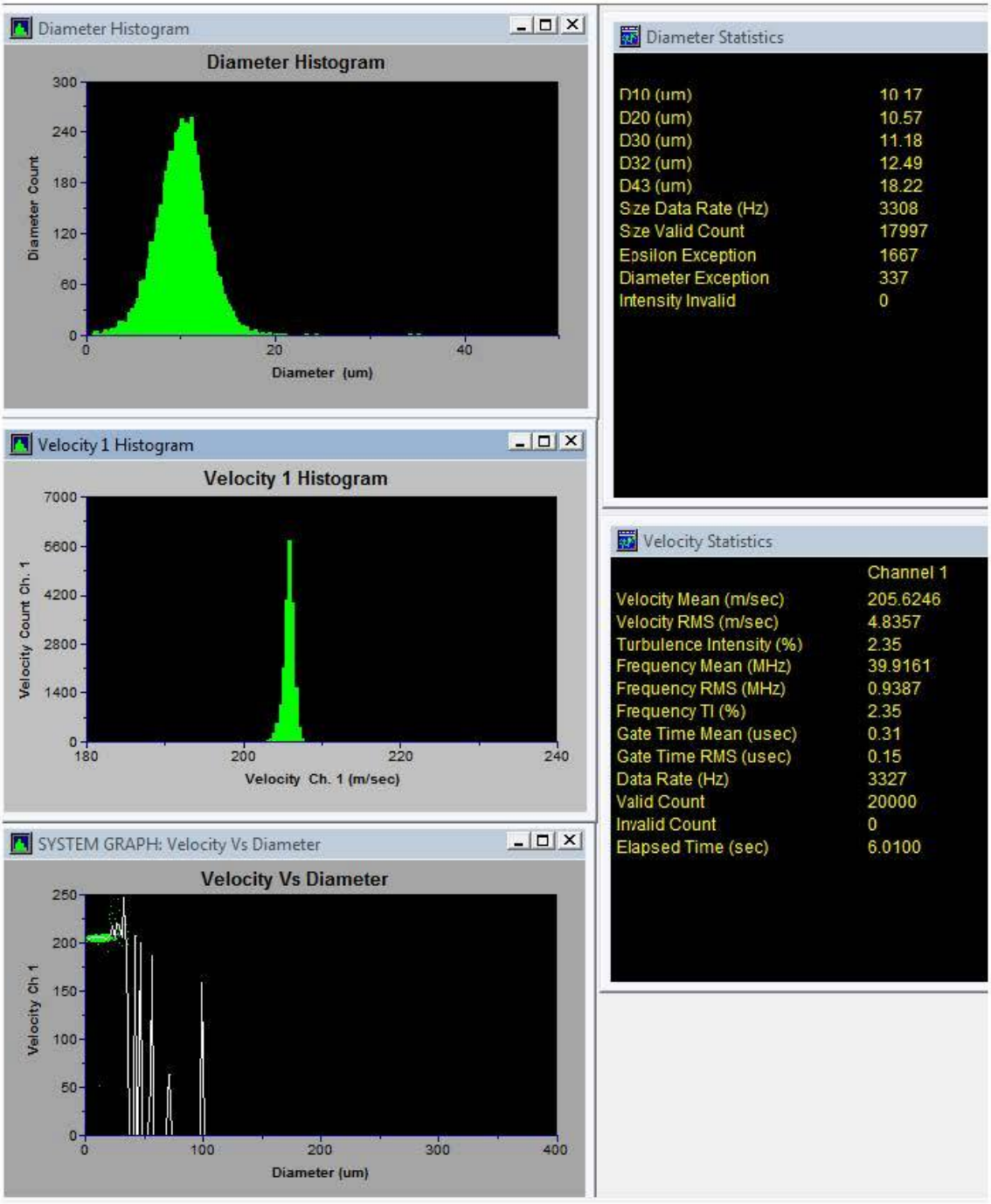
Measuring the sizes and mean velocity of the droplets were performed on the axis of the water jet at distance H = 10 mm and 20 mm from the nozzle. 20,000 droplets were measured at each point. Measurement results are presented in Figures and Table 2.

Note

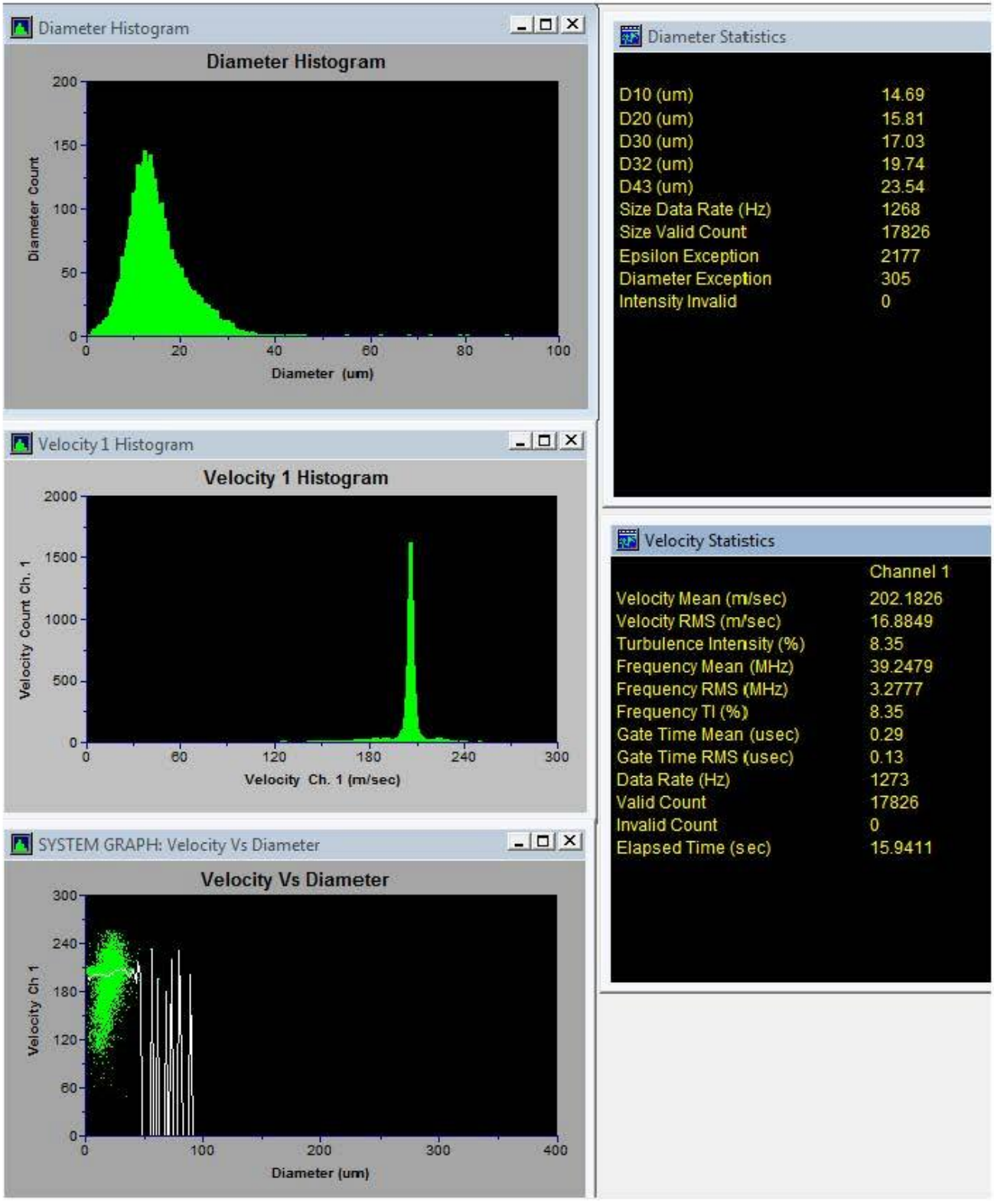
It should be indicated that the velocity field in the volume of the spray is highly turbulent and 3 dimensional.

The size and velocity histogram represents the information collected at a specific point downstream of the nozzle. The size histogram represents the global histogram of about 20,000 droplets of a wide diameter range and the velocity histogram represents the global histogram of all droplets of all size ranges at the specific location. However, each size group of the droplets has its own mean and RMS velocity values. These can be seen through the chart displaying the size to velocity correlation.

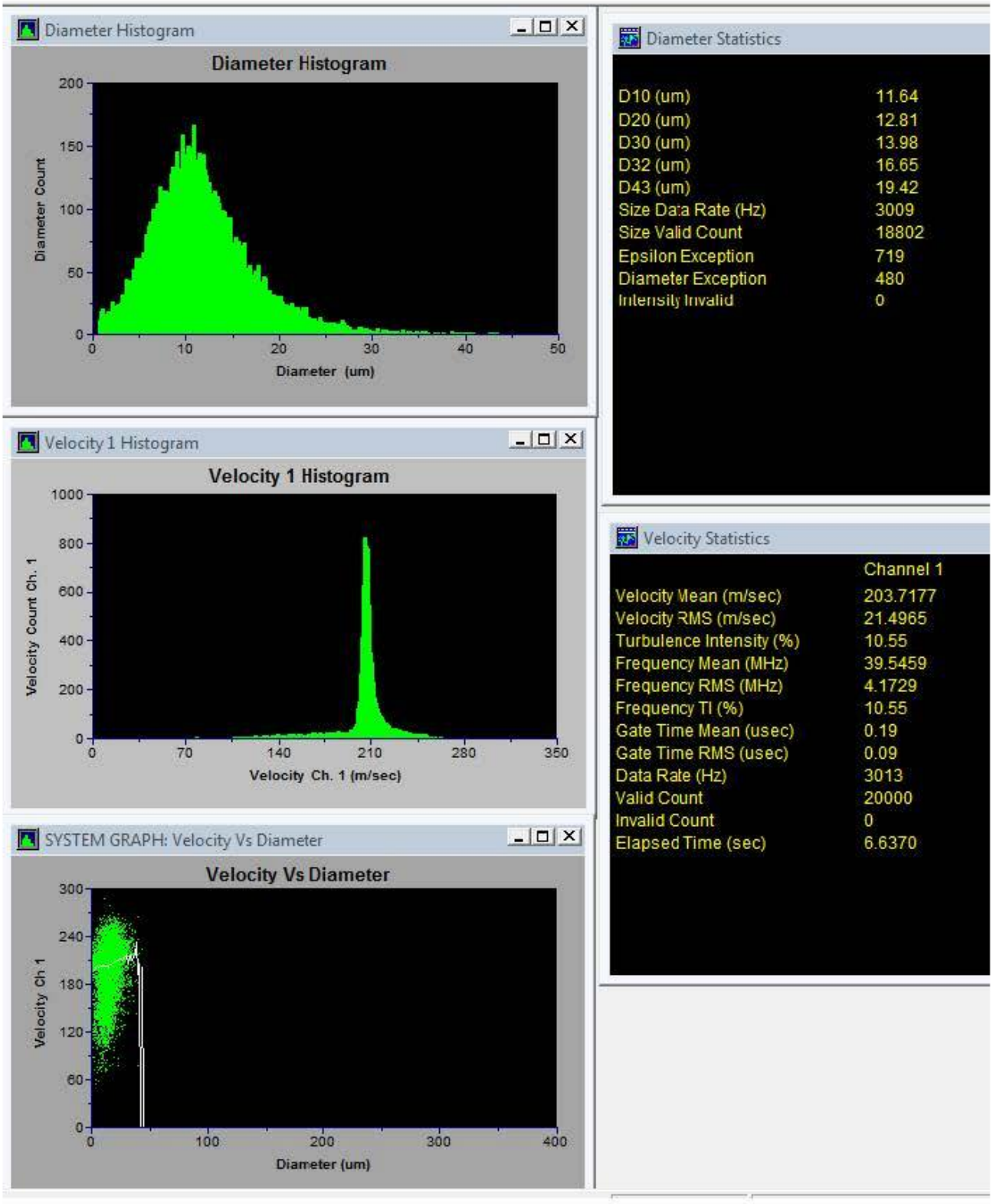
1. JP1-N23 handpiece, JetPeel device, air pressure ~95psi



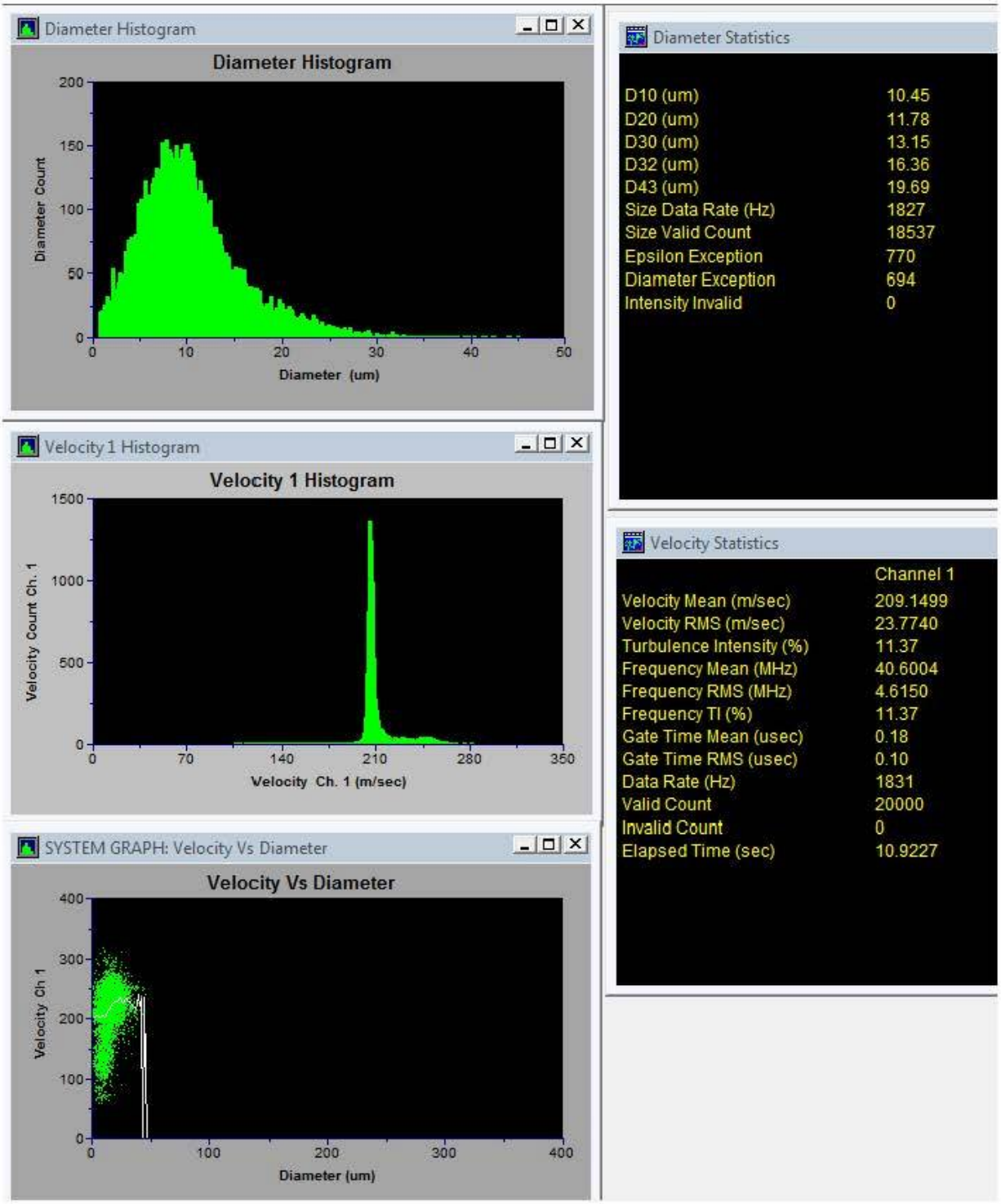
Run 11, H = 10mm


Diameter Histogram
Diameter Histogram
Diameter Count
Diameter (um)
Diameter Statistics
D10 (um) 14.69
D20 (um) 15.81
D30 (um) 17.03
D32 (um) 19.74
D43 (um) 23.54
Size Data Rate (Hz) 1268
Size Valid Count 17826
Epsilon Exception 2177
Diameter Exception 305
Intensity Invalid 0
Velocity 1 Histogram
Velocity 1 Histogram
Velocity Count Ch. 1
Velocity Ch. 1 (m/sec)
Velocity Statistics
Channel 1
Velocity Mean (m/sec) 202.1826
Velocity RMS (m/sec) 16.8849
Turbulence Intensity (%) 8.35
Frequency Mean (MHz) 39.2479
Frequency RMS (MHz) 3.2777
Frequency TI (%) 8.35
Gate Time Mean (usec) 0.29
Gate Time RMS (usec) 0.13
Data Rate (Hz) 1273
Valid Count 17826
Invalid Count 0
Elapsed Time (sec) 15.9411
SYSTEM GRAPH: Velocity Vs Diameter
Velocity Vs Diameter
Velocity Ch 1
Diameter (um)

Run 10, H = 20mm



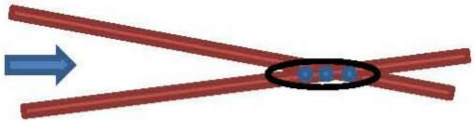
Run 28, H =10mm, glycolic acid 5% (n = 1.424). In experiment n = 1.33.

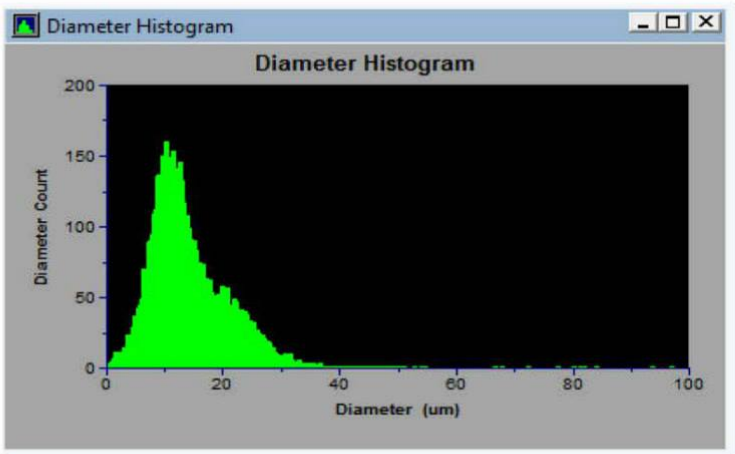


Run 29, H = 20mm, glycolic acid 5% (n = 1.424). In experiment n = 1.33.

2. JP1-N01 handpiece, JetPeel device, air pressure ~95psi

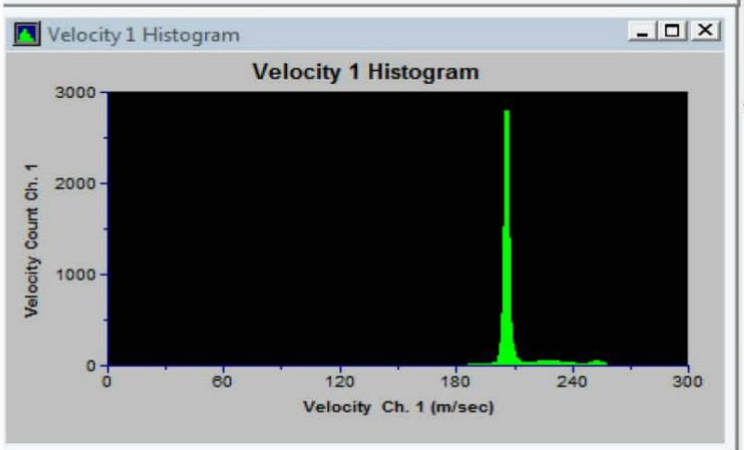
A) The laser control volume is located in the plane of three nozzles





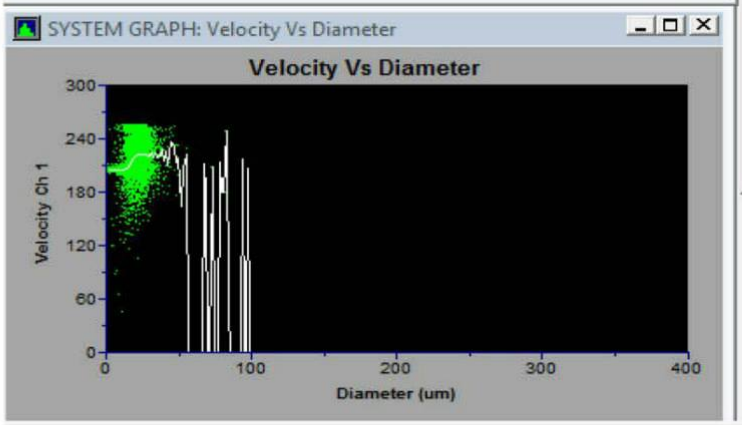
Diameter Statistics

D10 (um)	13.90
D20 (um)	15.32
D30 (um)	16.89
D32 (um)	20.54
D43 (um)	26.12
Size Data Rate (Hz)	777
Size Valid Count	20000
Epsilon Exception	3824
Diameter Exception	604
Intensity Invalid	0

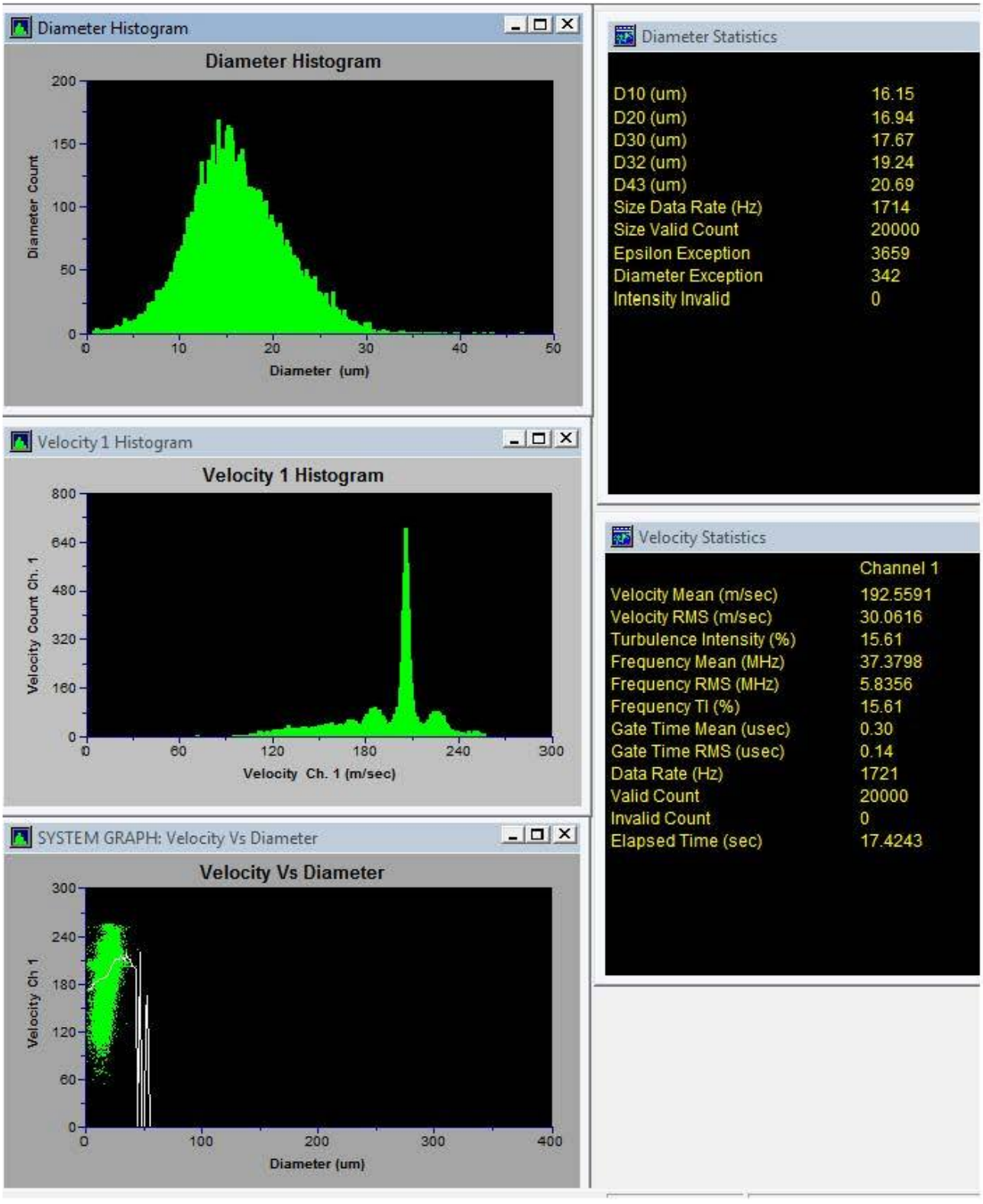


Velocity Statistics

	Channel 1
Velocity Mean (m/sec)	210.3157
Velocity RMS (m/sec)	13.4334
Turbulence Intensity (%)	6.39
Frequency Mean (MHz)	40.8267
Frequency RMS (MHz)	2.6077
Frequency TI (%)	6.39
Gate Time Mean (usec)	0.26
Gate Time RMS (usec)	0.11
Data Rate (Hz)	781
Valid Count	20000
Invalid Count	0
Elapsed Time (sec)	38.4012

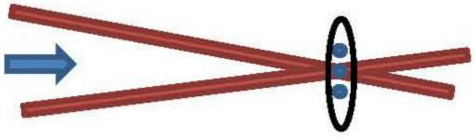


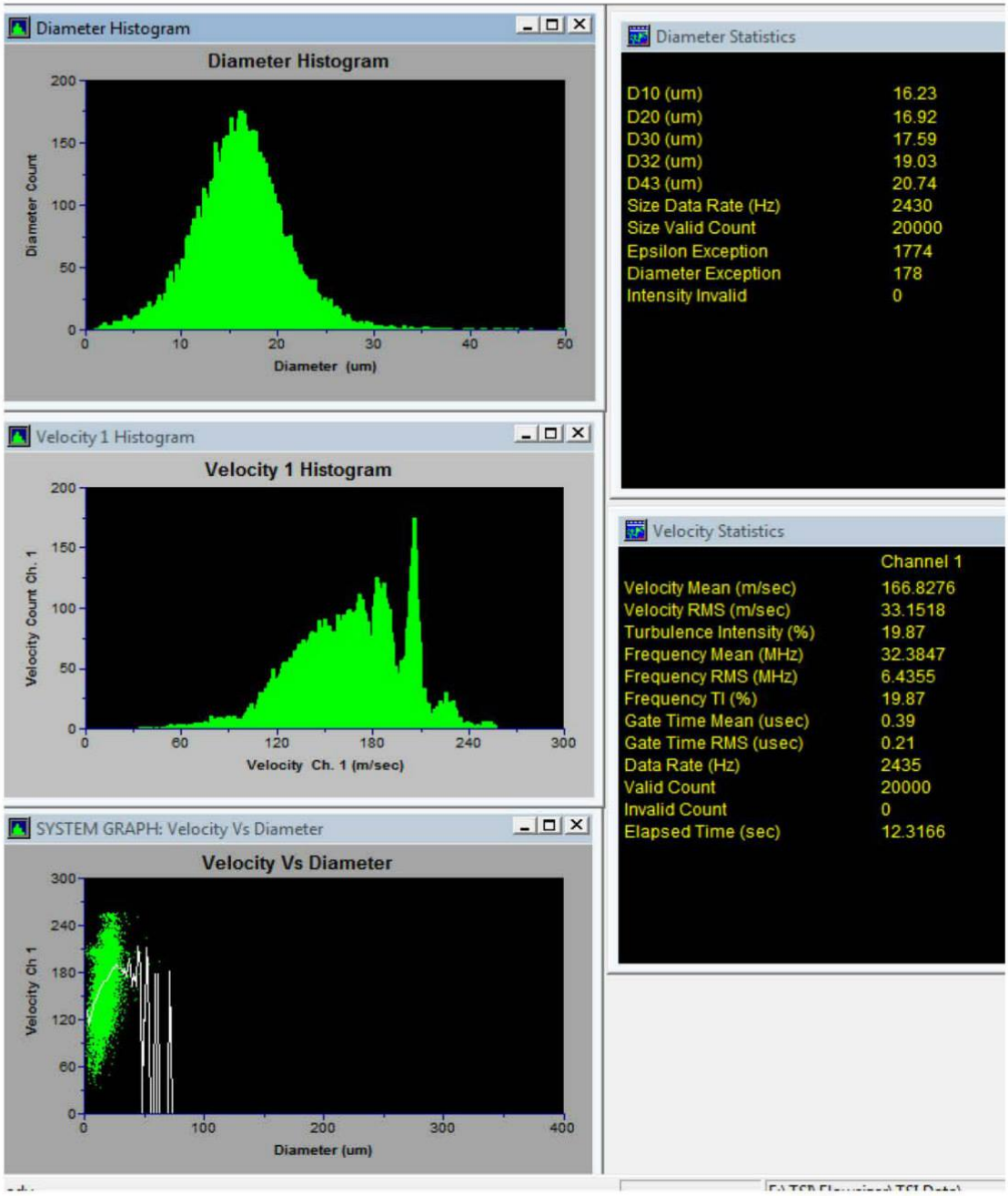
Run 14, H = 10mm


Diameter Histogram
Diameter Histogram
Diameter Count
Diameter (um)
Diameter Statistics
D10 (um) 16.15
D20 (um) 16.94
D30 (um) 17.67
D32 (um) 19.24
D43 (um) 20.69
Size Data Rate (Hz) 1714
Size Valid Count 20000
Epsilon Exception 3659
Diameter Exception 342
Intensity Invalid 0
Velocity 1 Histogram
Velocity 1 Histogram
Velocity Count Ch. 1
Velocity Ch. 1 (m/sec)
Velocity Statistics
Channel 1
Velocity Mean (m/sec) 192.5591
Velocity RMS (m/sec) 30.0616
Turbulence Intensity (%) 15.61
Frequency Mean (MHz) 37.3798
Frequency RMS (MHz) 5.8356
Frequency TI (%) 15.61
Gate Time Mean (usec) 0.30
Gate Time RMS (usec) 0.14
Data Rate (Hz) 1721
Valid Count 20000
Invalid Count 0
Elapsed Time (sec) 17.4243
SYSTEM GRAPH: Velocity Vs Diameter
Velocity Vs Diameter
Velocity Ch 1
Diameter (um)

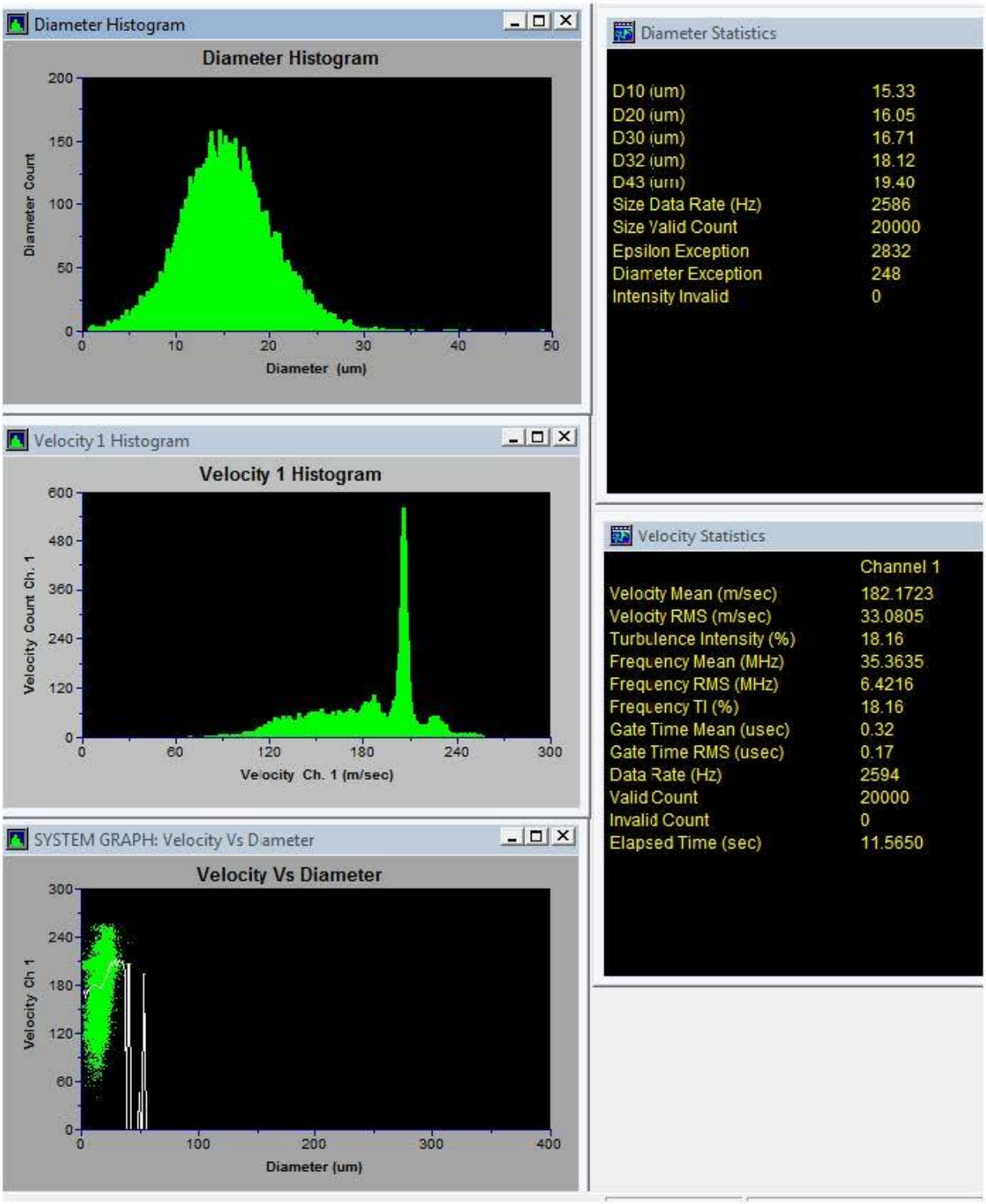
Run 13, H = 20mm

B) The laser control volume is located perpendicular to the plane of three nozzles



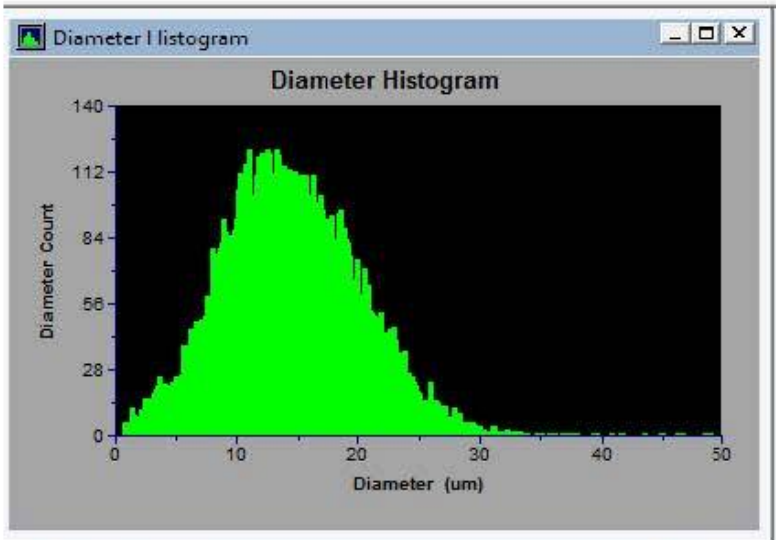


Run15, H =10mm

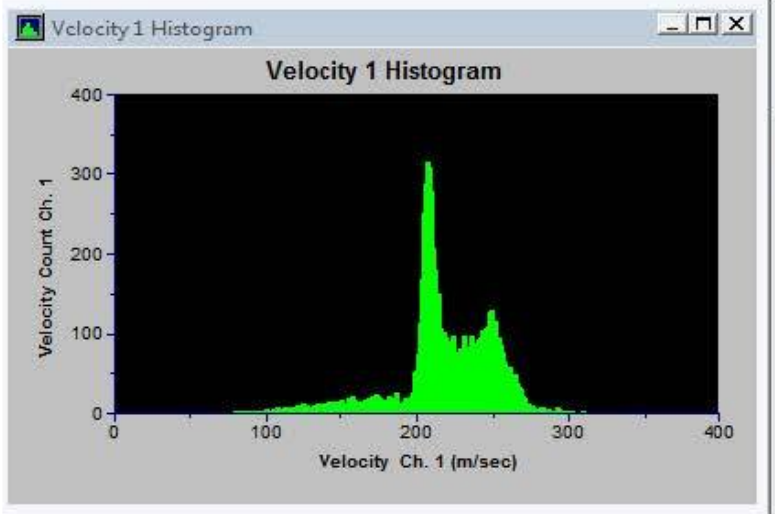

Diameter Histogram
Diameter Histogram
Diameter Count
Diameter (um)
Diameter Statistics
D10 (um) 15.33
D20 (um) 16.05
D30 (um) 16.71
D32 (um) 18.12
D43 (um) 19.40
Size Data Rate (Hz) 2586
Size Valid Count 20000
Epsilon Exception 2832
Diameter Exception 248
Intensity Invalid 0
Velocity 1 Histogram
Velocity 1 Histogram
Velocity Count Ch. 1
Velocity Ch. 1 (m/sec)
Velocity Statistics
Channel 1
Velocity Mean (m/sec) 182.1723
Velocity RMS (m/sec) 33.0805
Turbulence Intensity (%) 18.16
Frequency Mean (MHz) 35.3635
Frequency RMS (MHz) 6.4216
Frequency TI (%) 18.16
Gate Time Mean (usec) 0.32
Gate Time RMS (usec) 0.17
Data Rate (Hz) 2594
Valid Count 20000
Invalid Count 0
Elapsed Time (sec) 11.5650
SYSTEM GRAPH: Velocity Vs Diameter
Velocity Vs Diameter
Velocity Ch 1
Diameter (um)

Run 17, H =20mm

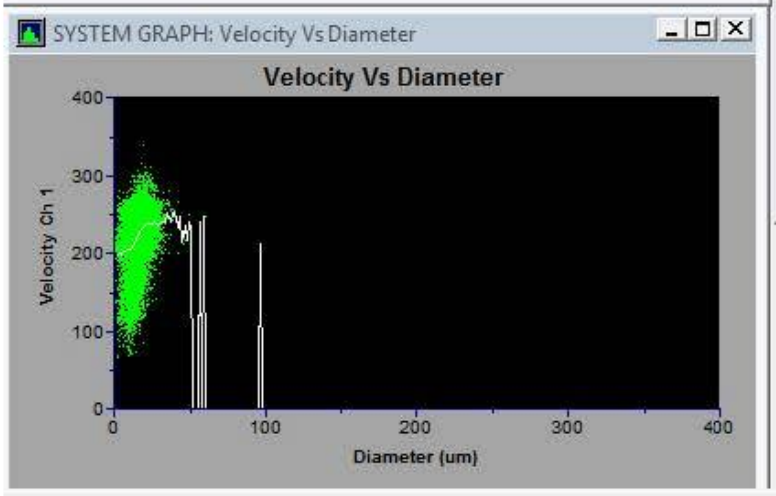
3. JP1-N05 handpiece, JetPeel device, air pressure ~95psi



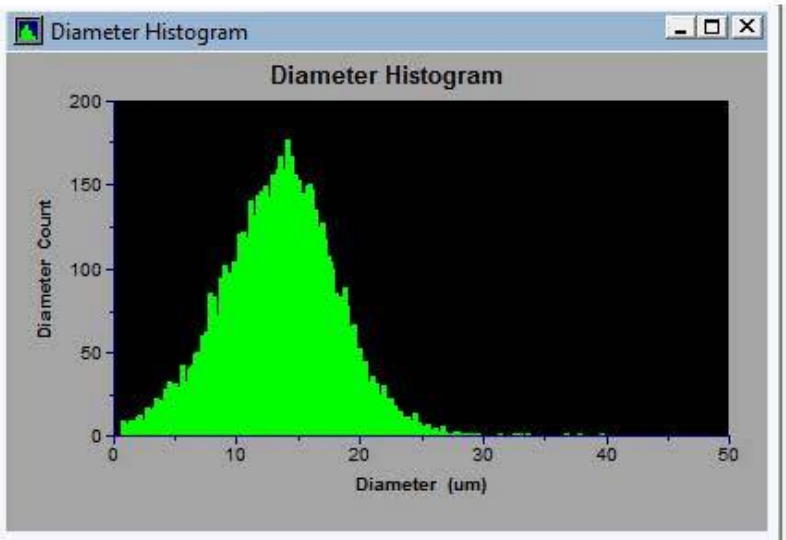
Diameter Statistics	
D10 (um)	14.44
D20 (um)	15.48
D30 (um)	16.46
D32 (um)	18.61
D43 (um)	21.16
Size Data Rate (Hz)	1780
Size Valid Count	18746
Epsilon Exception	987
Diameter Exception	268
Intensity Invalid	0

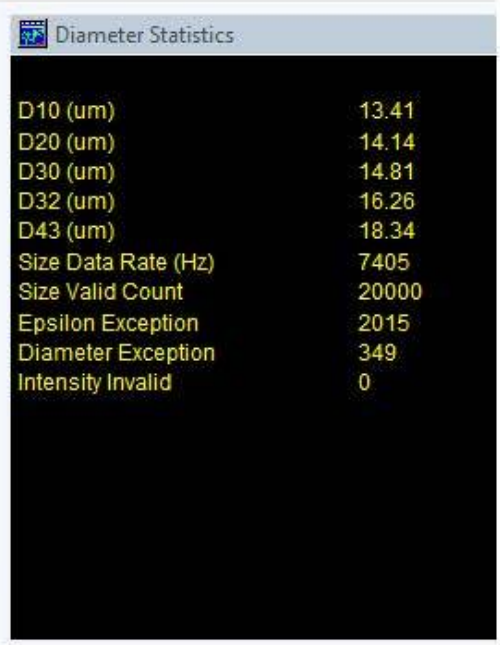


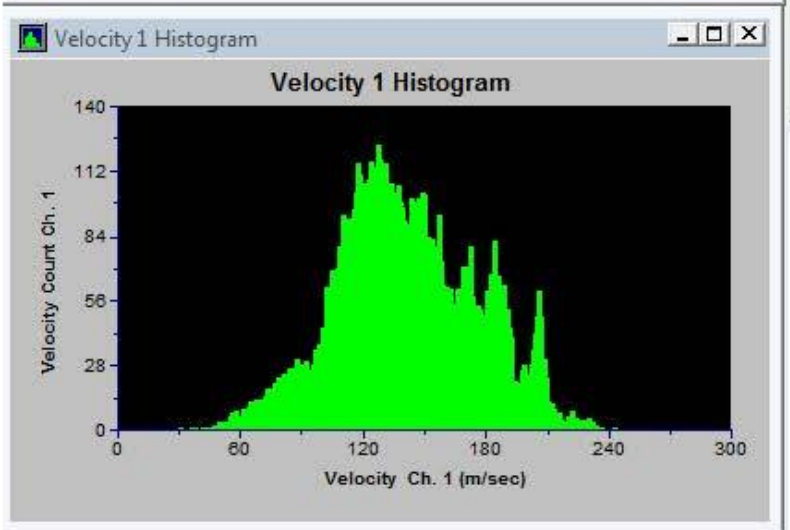
Velocity Statistics	Channel 1
Velocity Mean (m/sec)	219.2911
Velocity RMS (m/sec)	30.9562
Turbulence Intensity (%)	14.12
Frequency Mean (MHz)	42.5690
Frequency RMS (MHz)	6.0092
Frequency TI (%)	14.12
Gate Time Mean (usec)	0.19
Gate Time RMS (usec)	0.11
Data Rate (Hz)	1785
Valid Count	20000
Invalid Count	0
Elapsed Time (sec)	11.2006

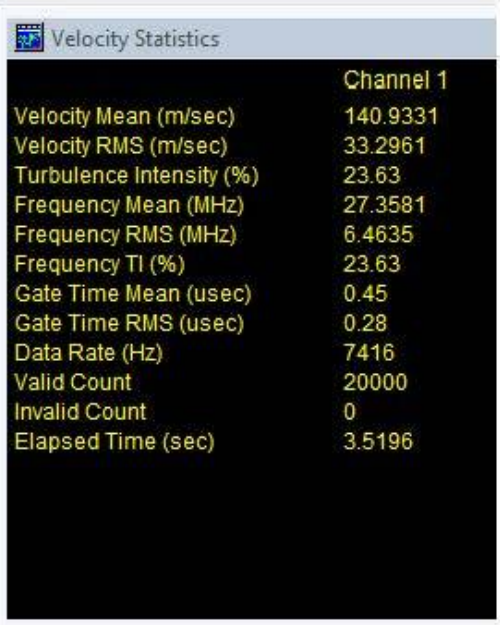


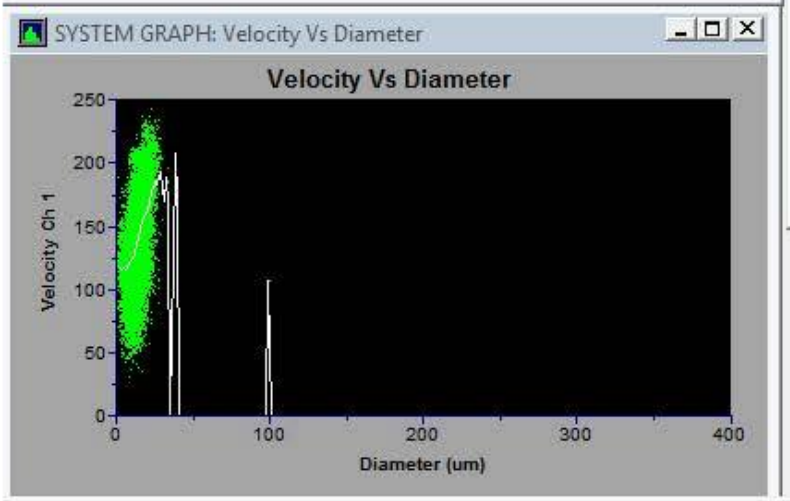
Run 23, H = 10mm


Diameter Histogram
Diameter Histogram
Diameter Count
Diameter (um)
0
50
100
150
200
0
10
20
30
40
50


Diameter Statistics
D10 (um) 13.41
D20 (um) 14.14
D30 (um) 14.81
D32 (um) 16.26
D43 (um) 18.34
Size Data Rate (Hz) 7405
Size Valid Count 20000
Epsilon Exception 2015
Diameter Exception 349
Intensity Invalid 0

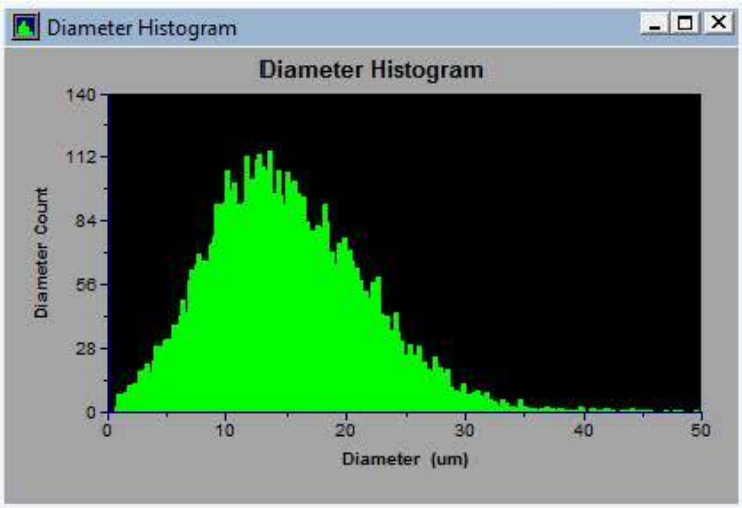

Velocity 1 Histogram
Velocity 1 Histogram
Velocity Count Ch. 1
Velocity Ch. 1 (m/sec)
0
28
56
84
112
140
0
60
120
180
240
300

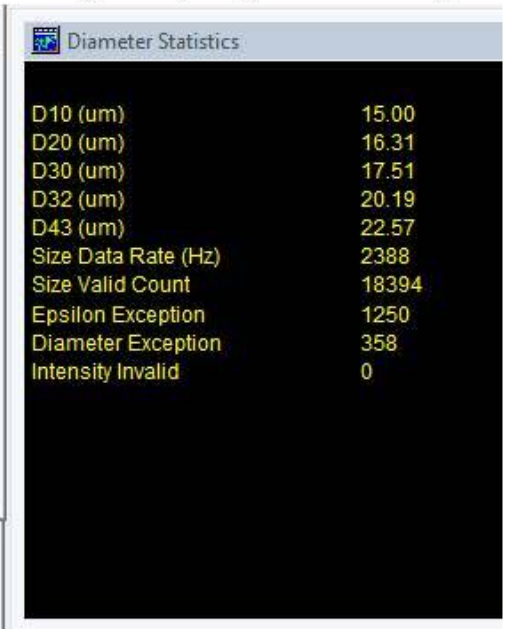

Velocity Statistics
Channel 1
Velocity Mean (m/sec) 140.9331
Velocity RMS (m/sec) 33.2961
Turbulence Intensity (%) 23.63
Frequency Mean (MHz) 27.3581
Frequency RMS (MHz) 6.4635
Frequency TI (%) 23.63
Gate Time Mean (usec) 0.45
Gate Time RMS (usec) 0.28
Data Rate (Hz) 7416
Valid Count 20000
Invalid Count 0
Elapsed Time (sec) 3.5196

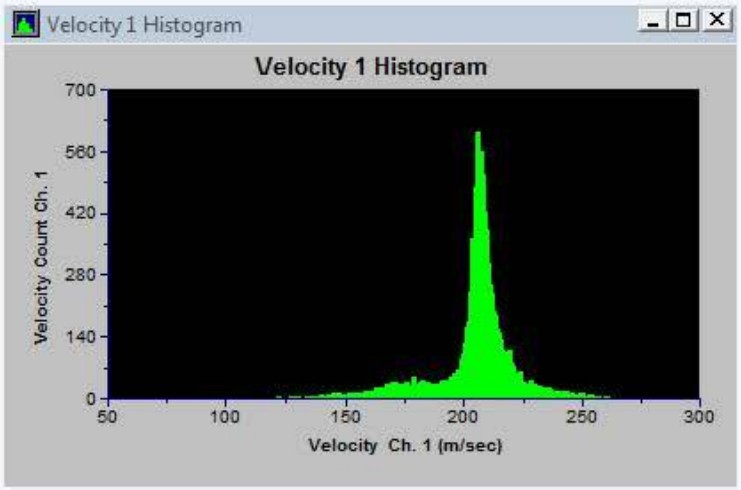

SYSTEM GRAPH: Velocity Vs Diameter
Velocity Vs Diameter
Velocity Ch 1
Diameter (um)
0
50
100
150
200
250
0
100
200
300
400

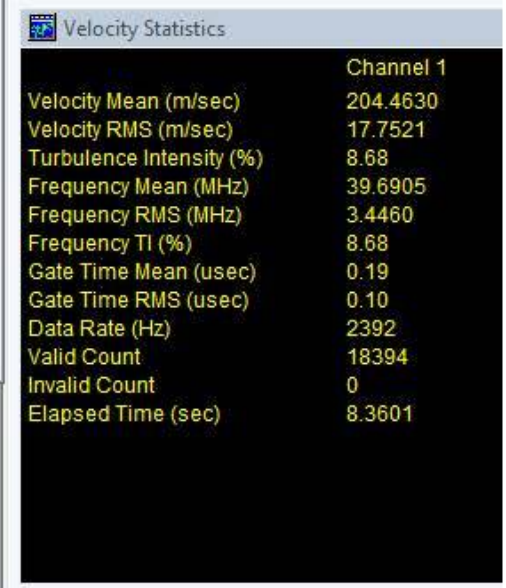
Run 19, H = 20mm

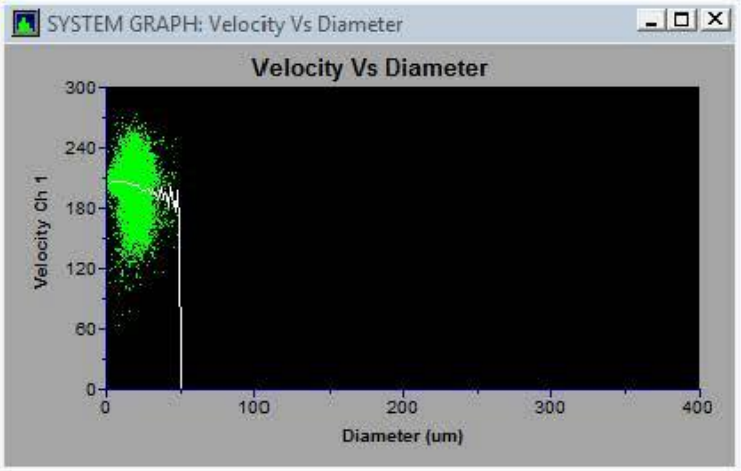
4. JND-011 Jetox-ND The cleansing and debridement system, air pressure ~50psi



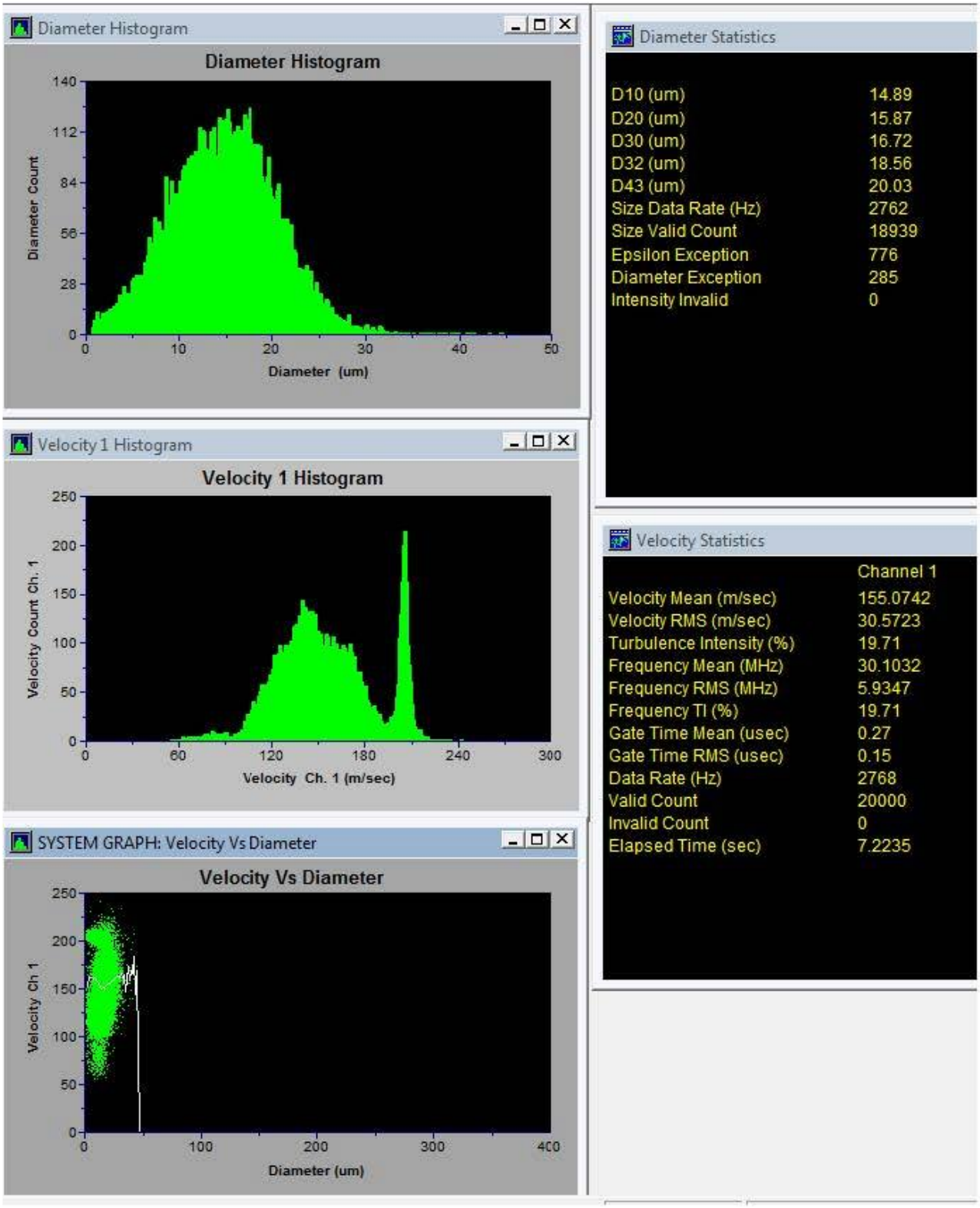






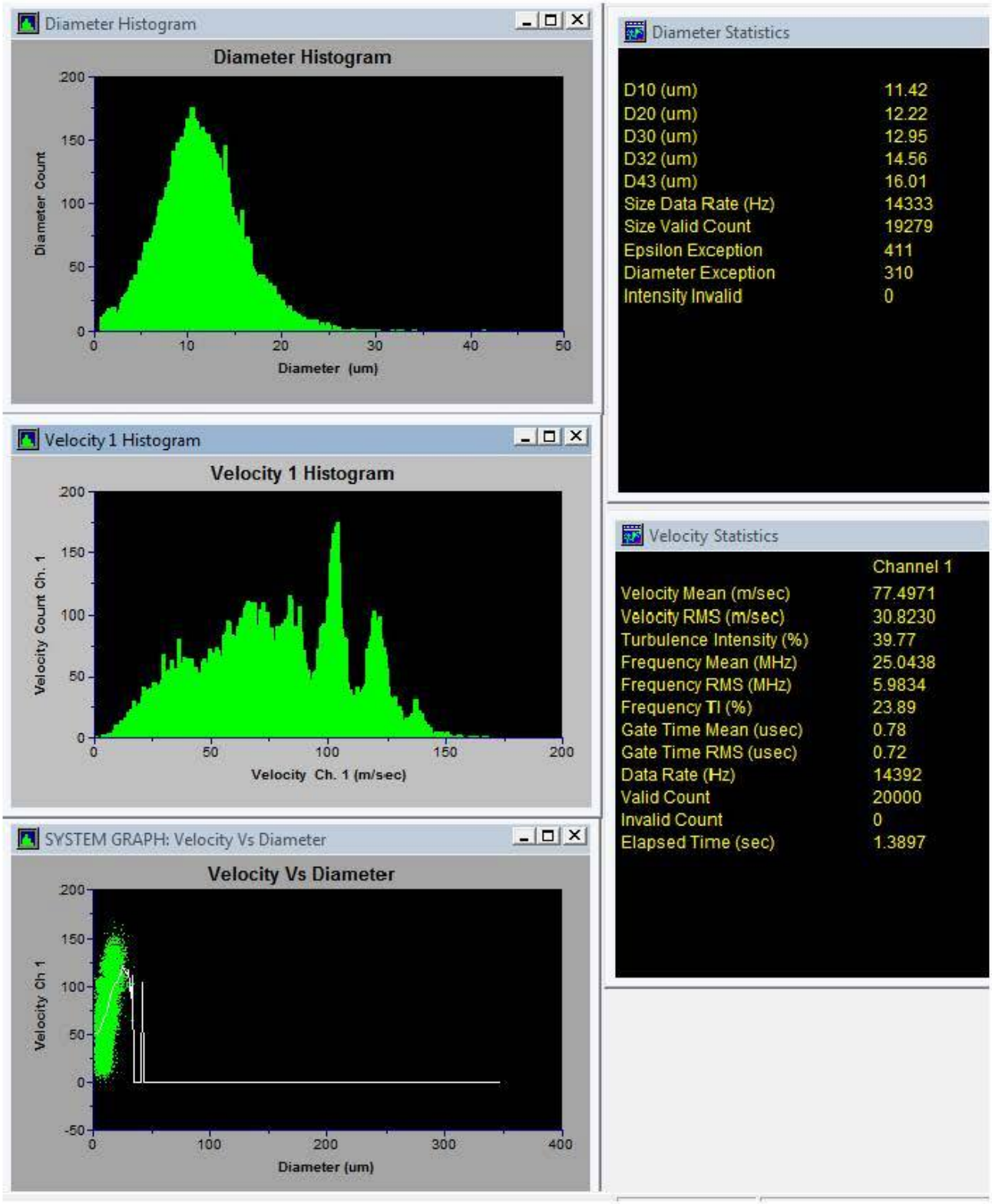


Run 25, H = 10mm

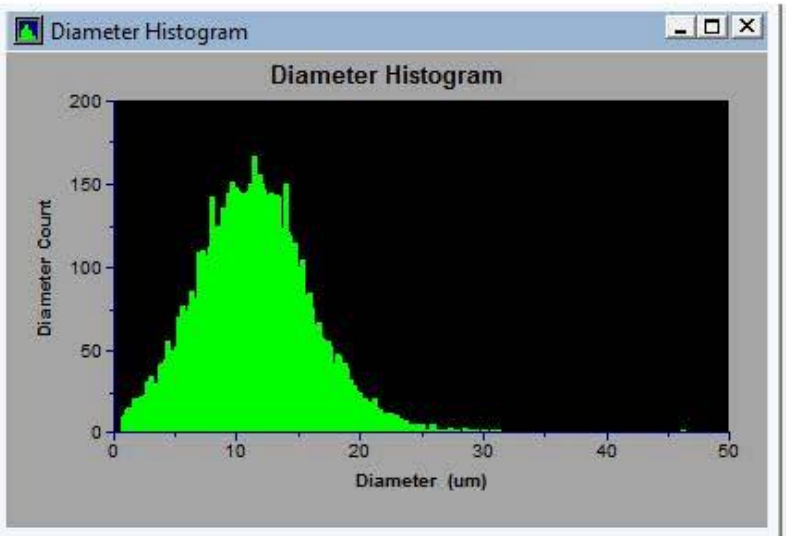

Diameter Histogram
Diameter Histogram
Diameter Count
Diameter (um)
Diameter Statistics
D10 (um) 14.89
D20 (um) 15.87
D30 (um) 16.72
D32 (um) 18.56
D43 (um) 20.03
Size Data Rate (Hz) 2762
Size Valid Count 18939
Epsilon Exception 776
Diameter Exception 285
Intensity Invalid 0
Velocity 1 Histogram
Velocity 1 Histogram
Velocity Count Ch. 1
Velocity Ch. 1 (m/sec)
Velocity Statistics
Channel 1
Velocity Mean (m/sec) 155.0742
Velocity RMS (m/sec) 30.5723
Turbulence Intensity (%) 19.71
Frequency Mean (MHz) 30.1032
Frequency RMS (MHz) 5.9347
Frequency TI (%) 19.71
Gate Time Mean (usec) 0.27
Gate Time RMS (usec) 0.15
Data Rate (Hz) 2768
Valid Count 20000
Invalid Count 0
Elapsed Time (sec) 7.2235
SYSTEM GRAPH: Velocity Vs Diameter
Velocity Vs Diameter
Velocity Ch 1
Diameter (um)

Run 24, H = 20mm

5. MJT-250 MedJet Irrigator, air pressure ~50psi

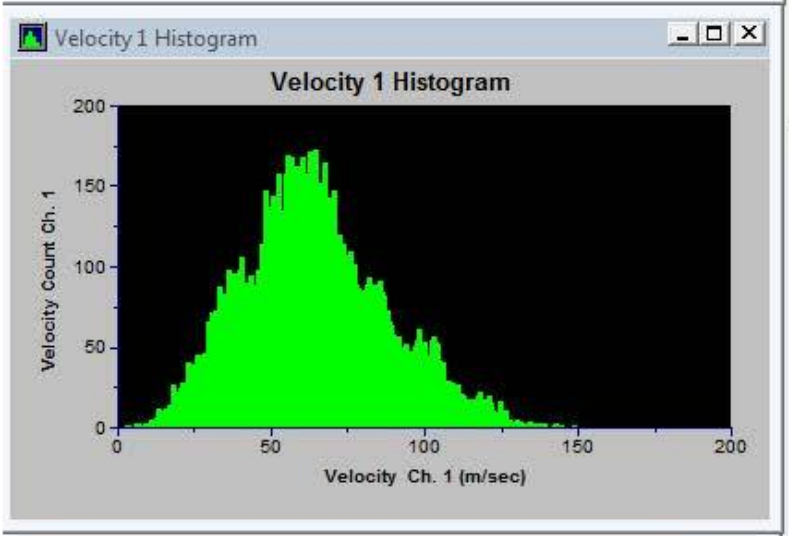


Run 34, H = 10mm



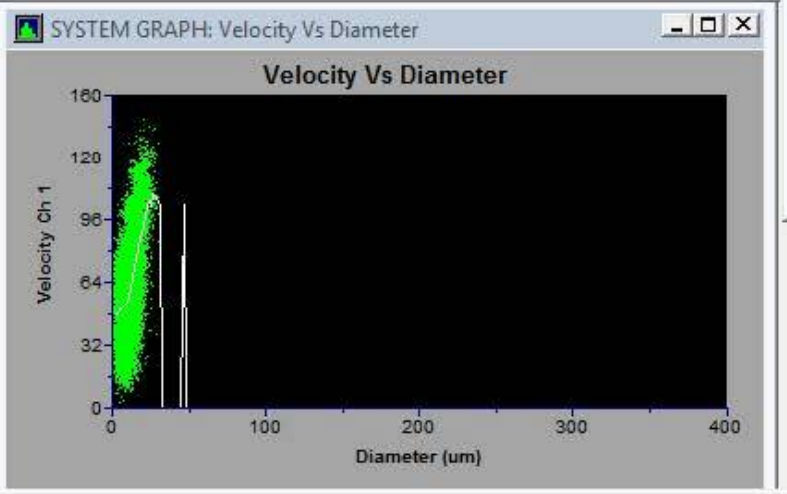
Diameter Statistics

D10 (um)	11.35
D20 (um)	12.20
D30 (um)	12.94
D32 (um)	14.57
D43 (um)	15.93
Size Data Rate (Hz)	24142
Size Valid Count	19273
Epsilon Exception	365
Diameter Exception	363
Intensity Invalid	0



Velocity Statistics

	Channel 1
Velocity Mean (m/sec)	63.9067
Velocity RMS (m/sec)	22.9355
Turbulence Intensity (%)	35.89
Frequency Mean (MHz)	22.4056
Frequency RMS (MHz)	4.4523
Frequency TI (%)	19.87
Gate Time Mean (usec)	0.94
Gate Time RMS (usec)	0.82
Data Rate (Hz)	24180
Valid Count	20000
Invalid Count	0
Elapsed Time (sec)	0.8271



Run 33, H = 20mm

Table 2 Spray parameters for different nozzles

		Nozzle	Liquid	H, mm	Run	D10, um	D32, um	Vel. Mean, m/s	Velocity RMS (m/s)
1	1	JP1-N23	Water	10	11	10.17	12.49	205.6	4.8
2		JP1-N23	Water	20	10	14.69	19.74	202.2	16.9
3		JP1-N23	glycolic acid 5%	10	28	11.64	16.65	203.7	21.5
4		JP1-N23	glycolic acid 5%	20	29	10.45	16.36	209.1	23.8
5	2	JP1-N01, parallel	Water	10	14	13.90	20.54	210.3	13.4
6		JP1-N01, parallel	Water	20	13	16.15	19.24	192.6	30.1
7		JP1-N01, perpendicular	Water	10	15	16.23	19.03	166.8	33.1
8		JP1-N01, perpendicular	Water	20	17	15.33	18.12	182.2	33.1
9	3	JP1-N05	Water	10	23	14.44	18.66	219.3	30.9
10		JP1-N05	Water	20	19	13.41	16.26	140.9	33.3
11	4	JND-011 Jetox-ND	Water	10	25	15.00	20.19	204.5	17.7
12		JND-011 Jetox-ND	Water	20	24	14.89	18.56	155.1	30.6
13	5	MJT-250 MedJet	Water	10	34	11.42	14.56	77.5	30.8
14		MJT-250 MedJet	Water	20	33	11.35	14.57	63.9	22.9