

AIAA-91-1381
LN_2 Spray Droplet Size Measurement Via Ensemble Diffraction Technique

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NASA

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Abstract

The size of subcooled liquified nitrogen droplets are measured with a 5 mW He-Ne laser as a function of pressure difference (ΔP) across flat spray and full cone pressure atomizing nozzles. For ΔP's of 3 to 30 psid the spray sauter mean diameter (SMD) ranged between 250 to 50 μm. The pressure range tested is representative of those expected during cryogenic fluid transfer operations in space. The droplet sizes from the flat spray nozzle were greater than those from the full cone nozzle. A power function of the form, $SMD \propto \Delta P^a$, described the spray SMD as a function of the ΔP very well. The values of 'a' were -0.36 for the flat spray and -0.87 for the full cone. The reduced dependence of the flat spray SMD on the ΔP was probably because of (1) the absence of a swirler that generates turbulence within the nozzle to enhance atomization, and (2) a possible increase in shearing stress resulting from the delayed atomization due to the absence of turbulence. The nitrogen quality, up to 1.5 percent based on isenthalpic expansion, did not have a distinct and measurable effect on the spray SMD. Both bi-modal and mono-modal droplet size population distributions were measured. In the bi-modal distribution the frequency of the first mode was much greater than the frequency of the second mode. Also, the frequency of the second mode was low enough such that a mono-modal approximation probably would give reasonable results.

Introduction

In the coming decades space-based cryogens will be needed to maintain life support, for propulsion, and for thermal control; these are three crucial elements of sustaining man's presence in space for long durations, i.e., Lunar/Mars Mission. Space-based crafts such as Orbit Transfer Vehicles, Lunar Transfer Vehicles, etc. will be needed for supporting man's activities. The reusability of these vehicles will require fuel resupply at regular intervals. The replenishment of depleted fuel tanks will be more cost effective than tank replacement.

Due to absence of buoyancy the replenishing of tanks in space is very different from replenishing under normal gravity. Liquid flow into a nonvented tank increases the tank pressure by compressing the vapor already existing in the tank. Since most systems in space are pressure driven, largely due to weight/cost factors, the pressure rise reduces the tank's final fill level. Venting, for pressure control, is not a viable option in space due to the possibility of expelling liquid overboard. Therefore, the replenishing of the space-based tanks with cryogens to high fill levels must be performed without venting while maintaining tank pressure at or below a pre-selected value. A filling technique known as No-Vent Fill (NVF) meets this challenge. This technique is being developed by the NASA Lewis Research Center as part of a continuing program to develop the technologies necessary for efficient management of space-based cryogens. Such management is critical to the success of man's activities in space.

In the NVF technique the existing quantity of the tank vapor is reduced by forcing most of the vapor to be condensed. The remaining vapor is capable of greater compression which means that higher fill levels can be achieved. The flow of cryogen as subcooled (relative to tank pressure) spray droplets into the tank vapor is the easiest and fastest means of achieving NVF objectives. The condensation on the surface of the spray droplets facilitates an increase in the

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tank fill level. This technique to promote condensation could be used to accomplish tank pressure control, also, and thus increase our capability to store cryogens for long durations. In such a tank pressure control scenario small quantity of tank liquid would need to be subcooled and recirculated into the tank vapor as mist (fine droplets) to force its condensation.

Pressure atomizing nozzles are used to generate such spray droplets. An unpublished analysis has been developed by the first author which models the condensation occurring on the spray droplets. The analysis shows that the spray droplet size significantly influences the condensation process. In the past the interest devoted to acquiring spray droplet size population information has mostly been done in pursuit of combustion and agricultural applications. Many authors have obtained such information using pressure atomizing nozzles.[1-4] Although an extensive data base is available for storable fluids no data is found for atomization of cryogens via pressure atomizing nozzles.

This paper presents the results of droplet size population measurements of subcooled liquid nitrogen generated by two pressure atomizing nozzles having very different flow patterns. Since the three liquid parameters important in atomization, namely surface tension, absolute viscosity, and density, are similar for nitrogen and oxygen the results presented here for nitrogen should be applicable to oxygen atomization through pressure nozzles, as well. The droplet sizes are gathered by an instrument based on diffraction of light from a low power He-Ne laser beam. The range of pressures covered in the experiment is representative of those expected during fluid transfer operations in space.

Experimental Equipment

The design goal was a simple apparatus having the minimum attainable heat leak into the tank. Additional requirements of the apparatus were that it must allow easy nozzle replacement, adequate visual observation of the spray, and have a direct optical path to the spray for using a low power laser beam.

Tank

The top and elevation views of the experimental tank configuration are shown in Figs. 1(a) and (b). The schematic of Fig. 2 shows that the test tank is immersed in a LN_2 primary bath, and is supported by two pipe segments each of which extend from the tank wall through the primary bath and the primary bath vacuum jacket to the outside. These pipes are placed directly opposite to each other to allow passage of the laser beam. The primary bath is vacuum jacketed to reduce boil off and the pipes are submerged in secondary baths. These secondary baths, silver brazed to the outside wall of the primary bath vacuum jacket, are insulated with urethane foam. A quartz window view port assembly in the top of the test tank allows visual access to the spray. A bronze mesh screen is placed in the test tank bottom to inhibit spray splashing, which would alter the droplet measurement. All apparatus is type 304 stainless steel except as shown in Fig. 2.

Flow System

Liquified nitrogen was pressure transferred into the test cell via a vacuum jacketed supply line from a remotely located 300 gal dewar. Inside the test cell the supply line split into two nonvacuum jacketed lines (the primary bath line and the spray line) as shown in Fig. 2. The primary bath line flow was controlled by a hand operated globe valve and was used to fill the primary bath. A secondary bath line (not shown), connected to the primary bath line, was used to fill the secondary baths. The flow through the secondary bath line was also controlled by a hand operated globe valve located downstream of the secondary baths. The spray line flow was controlled by a globe valve. The spray line was immersed in the primary bath for a distance of 30 ft prior to entering the test tank.

Two gravity drain lines were used to help control the cryogenic liquid. The first, namely the tank drain line, was open to atmosphere. A check valve prohibited any backflow into the test tank. The second, namely the primary bath drain line, was also open to atmosphere downstream of a globe shutoff valve. This line prevented the primary bath from over filling. The secondary baths drained into the primary bath. This was easily accomplished since flow into secondary baths was pressure driven and the inlet and outlet ports were both located on top of the secondary baths.

The volumes of the primary bath vacuum jacket, and the laser and receiver tubes were connected in parallel to an oil sealed mechanical vacuum pump. The pump capacity was 45 μm. In case of vacuum failure the jacket and tubes could be individually isolated to determine the failed section. Either tube could be checked separately by connecting it to the pump.

Instrumentation

The instrumentation schematic, Fig. 3, superimposes the instrumentation on the flow schematic. The temperature of the spray line flow was measured to within ±0.1 °R by a Resistance Temperature Detector (RTD) located approximately 8 in. upstream of the nozzle. A total of 5 RTD's, spaced at approximately 6 in. intervals, measured the tank vapor temperature to within ±0.1 °R. Test tank and spray line pressures were sensed by strain-gage type pressure transducers to within ±0.2 psia. All temperatures and

pressures were measured at approximately 2.5 sec intervals. A thermionic gage was used to measure the vacuum level in the jacket and the laser/receiver tubes.

Test Article

Two pressure atomizing spray nozzles, one giving a flat spray and one giving a full cone spray, were used in this experiment. The spray pattern for the flat spray is filled ellipse and that for the full cone is filled circle when viewed from the top. The flat spray nozzle was turned such that the major axis of the ellipse was perpendicular to the laser. The manufacturer* lists the spray angles, and orifice diameters (using water at 20 psid) as 53°/0.053 in. and 65°/0.062 in. for the flat spray and full cone nozzles, respectively. Both nozzles are of 304 stainless steel construction. The flat spray nozzle was designated as TP-6504 and the full cone nozzle as TG-3 by the manufacturer. Figures 4(a) and (b) show these nozzles. Visible along side the full cone nozzle is its internal swirler.

Laser

The spray droplet size measurements were taken with a Malvern 2600 Particle Analyzer.† Different models of this instrument were used by the previously cited authors[1-4] in their studies. The instrument is based on Fraunhofer diffraction theory basics of which can be found in Ref. 5. A low power (5 mW) He-Ne laser is used to illuminate a region where the particle sizes are to be measured. At any given instant, the particles, despite their movement, give a stationary diffraction pattern by diffracting the incident laser light. The diffraction pattern does vary, however, according to the instantaneous size distribution of particles as they move across the illuminated region.

The diffraction patterns are focused on a series of concentric photo-electric half-detectors that produce analogue signals proportional to the received light intensity. A Fourier transform lens is used for focusing. Integration of the diffraction patterns over a suitable period, during which there is a constant particle flux, gives an average diffraction pattern. The diffraction patterns are read and the integration is performed by a desk-top computer connected to the detectors. The computer also calculates a size distribution by using the method of nonlinear least squares analysis. This gives a diffraction pattern closest to the average diffraction pattern. In this experiment 200 diffraction patterns, taken over a total of 8 sec, were integrated.

To obtain useful results it is necessary, prior to obtaining the particle size data, to make a measurement through the same environment as that experienced by the particles but with the particles removed from the laser path. The data obtained is called the "background" data and it measures the stray diffraction due to scattering from the environment surrounding the particles, misalignment of the laser, etc. Minimal "background" diffraction is preferred. After obtaining the "background" data the particles are placed in the laser path and measurements are taken again. This data is called the "signal" data because it includes the diffraction by the particles and the "background" diffraction. The "signal" data is corrected for the "background" data with the result being called the "derived" data. Only the "derived" data is used in determining the particle sizes. More detailed information about the principle of operation of this instrument may be found in Ref. 6. Discussion of its accuracy and limitations may be found in Ref. 7.

The evacuated tubes for the laser and receiver sides as shown in Fig. 2 allowed laser alignment with little difficulty at the nominal operating tank temperature of 140 °R. (Alignment difficulties are encountered due to vapor density gradients along the laser path.) The tank end of the each tube was fitted with an anti-reflection coated quartz window, and the outside end with the laser and receiver lenses. The beam alignment was acceptable after the tank vapor had cooled to saturation.

Data Acquisition

Pressure and temperature measurements as voltage signals from the various sensors were remotely transmitted to an ESCORT II data acquisition system at the Lewis Laboratory's Research Analysis Center. A data acquisition program written specifically for the facility provides for data acquisition and recording, on line data display, limit checking, performance calculations, graphics, and history files.

The droplet size and its distribution are calculated by the desk-top computer. The computer calculates, on percent by weight basis, the droplets in 15 discrete size ranges for the 300 mm Fourier transform lens used. It also calculates the volume mean diameter (VMD or D_{43}), the sauter mean diameter (SMD or D_{32}), $D_{10\%}$, $D_{50\%}$, and $D_{90\%}$. This information is available within one to two minutes after a data scan is taken and can be used to control the experiment. The results presented are for SMD's since they are most often sought for. The capability of the available optics to measure particle sizes was from 5 to 565 μm.

Experimental Procedure

The experimental procedure presented herein was followed to insure minimum "background" diffraction when tank and its vapor had reached the nitrogen saturation temperature at one atmosphere. Initially, the tank, primary

*Spraying Systems, Co. Wheaton, IL.
†Malvern Instruments, Malvern, England.

bath vacuum jacket, and the laser/receiver tubes were at room temperature and contained air at one atmosphere pressure. The experimental procedure began by inserting the tubes into the pipe segments and sealing them to the same segments with flexible sleeves. After insertion, vacuum was drawn in the primary bath vacuum jacket and in the tubes to approximately 45 μm. Then laser was aligned and an initial "background" data was taken to insure that the insertion of the tubes into the pipes, and subsequent drawing of the vacuum, did not affect the integrity of the lenses or the quartz windows.

The air and moisture were purged from the tank by using room temperature nitrogen gas. The purge continued for approximately one hour after which the filling of the primary bath was started. Only after the primary bath was filled was the spray started to further assist in cooling the tank vapor while still preventing tank overpressurization. Only after the tank had sufficiently cooled down, evident from the large reduction observed in the primary bath boil off, were the secondary baths filled. This was done to avoid unnecessary thermal shocks and pressure pulses within the secondary baths.

After the tank had completely cooled the spray was stopped. Because the spray was positioned near the center of the tank the vapor near the top was slightly superheated. To bring the entire vapor mass to saturation temperature some LN_2 was trickled through the test tank vent line back into the test tank volume. The trickle was stopped when all the vapor RTD's indicated saturation temperature. The final "background" diffraction pattern was then measured. Immediately after this measurement the spray was started again and the droplet sizes were measured as a function of increasing nozzle pressure differentials.

Results and Discussion

All data was analyzed with model-independent size distribution to eliminate any bias toward curve fitting the data to a particular distribution type. The Analyzer reported the droplet size distribution in the forms of "Cumulative Percent Undersize Volume (weight) Distribution" and as "Volume (weight) Frequency Distribution." The first form gives information about the percent volume of droplets below a given size. This information was analyzed using numerical integration and interpolation to derive the spray droplet sizes. Figure 5(a) is a representative example of the first form from this experiment. The data shown is for 20 psid across the flat spray nozzle. The second form represents the percent by volume (weight) of droplets within a given range of sizes and is used to evaluate the size distribution. Figure 5(b), generated from Cumulative Percent Undersize Volume information, is a representative example of the narrow weight frequency distribution in this experiment. It is seen here that the distribution is skewed to one side. This is typical of sprays. The figure represents a bi-modal distribution with the frequency of the first mode being much greater than the frequency of the second mode. It is also seen that the frequency of second mode is low enough that a mono-modal approximation probably would give reasonable results. It is not unreasonable to expect some variation in the distribution as completely identical size distributions are rare. Indeed, some mono-modal size distributions were recorded. But, since calculation of the size distribution did not assume any specific model, and since the second mode frequencies were low, the SMD's were not expected to be influenced by the presence of these modes. This is supported from the data by comparing the SMD's at same pressure difference (ΔP's) across the nozzles for the two mode types.

The droplet size information was taken 2 in. below the discharge surface of the full cone nozzle and 2.75 in. below that of the flat spray nozzle. These distances were chosen to help keep quartz windows dry. The flat spray nozzle discharge surface was located higher than that of the full cone nozzle to insure that the spray atomization process was completed before the spray reached the measurement region.

The influence of the ΔP across the nozzle on the SMD is shown in Figs. 6(a) and (b) for the flat spray and full cone nozzles, respectively. The numerical values of the SMD data with the nozzle pressure is shown in Table 1. It is seen here that the droplet SMD decreases with increasing ΔP. This was as expected. For both nozzles the measurements were made horizontally through the center of the spray. The horizontal centerline measurements are generally preferred because both the small droplets in the spray core region and the large droplets away from the core are considered.

A regressional analysis was performed using the least-squares method on the SMD and the ΔP for each nozzle. It was found that a power function of the form $SMD \propto \Delta P^a$ described this data very well. The value of 'a' was -0.36 for the flat spray data and -0.87 for the full cone spray data. Hautman[8] shows that the exponent values from earlier works using pressure swirl injectors ranged between -0.2 to -0.5. Dodge and Biaglow[3] determined the exponent value to be -0.86 for a simplex swirl injector. Hautman[8] determined the exponent to be -0.59 for an injector producing hollow cone spray pattern.

The flat spray SMD's reduced dependence on the ΔP may be explained as follows. The ΔP influences the shearing stress on the liquid outside the nozzle and the turbulence within the nozzle. An increase in ΔP increases the shearing stress and the turbulence, which in turn, cause better atomization and yield smaller droplets. Unlike the full cone nozzle the flat spray nozzle did not have a turbulence generating device (swirler). Therefore, it is very likely that the

flow was much less turbulent approaching the flat spray nozzle orifice than it was when approaching the full cone nozzle orifice. The reduced turbulence decreased the significance of ΔP on the atomization through the flat spray nozzle. The reduction in turbulence is also probably what caused the delayed atomization for the flat spray nozzle and forced it to be located higher than the full cone nozzle. It is speculated that the spray from the flat spray nozzle experienced greater shear stress due to the increased distance and that further reduced the significance of ΔP on the atomization through this nozzle.

Obviously, the simple regressional equations presented here do not serve to explain the physics of spray atomization, a task that has been attempted by many researchers with little success. But they do shed some light on the influence of ΔP and on why the influence may vary between different flow pattern nozzles.

Several tests were conducted on each nozzle to check the reproducibility of data. Sufficient time was provided between tests to allow the entire system to reach room temperature. The reproducibility of the measuring system is acceptable as seen in Figs. 6(a) and (b). Visual observations indicated the spray thickness to be smaller at the measuring location for the flat spray nozzle than it was for the full cone nozzle. This probably caused the obscuration to be higher for the full cone nozzle than with the flat spray nozzle and resulted in slightly higher scatter in the full cone data. An obscuration level is a measure of reduction in laser intensity reaching the photo-electric half detectors. It ranges between 1 and 0 for complete and no reduction, respectively.

All visual observations made during the testing showed a whitish spray suggesting high droplet density. The laser absorption and multiple diffraction by the spray droplets caused high levels of beam obscuration. In the present experiment the obscuration level varied between 0.46 and 0.99 (Table 1). Such levels are not uncommon[3,8] for diffraction type instruments measuring spray droplet size distribution. An approach described by Felton[9] as used by Cohen[10] to correct the SMD for obscuration was used. A range of correction factors (corrected SMD / measured SMD) was calculated for high obscuration levels and narrow weight-frequency distributions. This was necessary because the model-independent distribution could not be used to correct each data point since Felton's[9] procedure corrects the Rosin-Rammeler distribution parameters only. This range was calculated to be between 1.05 to 1.15 indicating that even in worst conditions the true SMD would only be approximately 15 percent greater than the measured SMD.

The average spray temperature, measured by the spray line flow RTD, for the entire test series was within 1 ^{o}R of saturation at tank pressure, which was nearly atmospheric. This restricted liquid flashing to very small quantities. The maximum quality for the entire series was 1.5 percent based on isenthalpic expansion. However, for most tests, either the quality was less than 1.0 percent or flashing did not occur. The small qualities were not expected to have significant influence on the SMD. The comparison of the SMD's at the same ΔP's for various qualities showed that the qualities encountered in this experiment did not have a distinct and measurable influence.

The laser side quartz window remained clean during all tests. This is attributed to its small size which facilitated better sealing. This was not true for the receiver side because ice and oil were occasionally found deposited on the vacuum-side surface of the receiver quartz window. This contimination caused severe beam blooming and steering and resulted in less than optimum "background" data. Occasionally, the pressure on the spray line fluctuated making it difficult to connect the size measurement to ΔP across the nozzle. To realize useful results each data point from the entire test series was scrutinized using all available information. This resulted in discarding some data points. The data is presented without correction for obscuration.

Summary

The droplet sizes of subcooled liquid nitrogen as a function of pressure differential across both a flat spray and a full cone pressure atomizing nozzle were measured using a laser diffraction based instrument. The measurements were obtained using a 5 mW He-Ne laser beam which passed through a test tank volume and was focused onto a receiver. The use of evacuated tubes for the laser and receiver sides allowed laser alignment with little difficulty. For all ΔP's across the nozzles the SMD's of droplets measured for the flat spray were greater than the SMD's of droplets measured for the full cone. A power function of the form, $SMD \propto \Delta P^{a}$, described the spray SMD as a function of the ΔP very well. The values of 'a' were -0.36 for the flat spray and -0.87 for the full cone. The reduced dependence of the flat spray SMD on ΔP is probably because of (1) the absence of a swirler that generates turbulence within the nozzle to enhance atomization, and (2) a possible increase in shearing stress resulting from the delayed atomization due to the absence of turbulence.

Both bi-modal and mono-modal droplet size population distributions were measured. In the bi-modal distribution the frequency of the first mode was much greater than the frequency of the second mode. But, the frequency of the second mode was low enough that a mono-modal approximation probably would give reasonable results. The data also showed that nitrogen quality, up to 1.5 percent based on

isenthalpic expansion, did not have a distinct and measurable influence on spray SMD's. The extension of this work includes different sizes of similar nozzles, hollow cone spray, and the effect of quality greater than 1.5 percent.

Since the three liquid parameters important in atomization, namely surface tension, absolute viscosity, and density, are similar for nitrogen and oxygen the results presented here for nitrogen should be applicable to oxygen atomization through pressure nozzles, as well.

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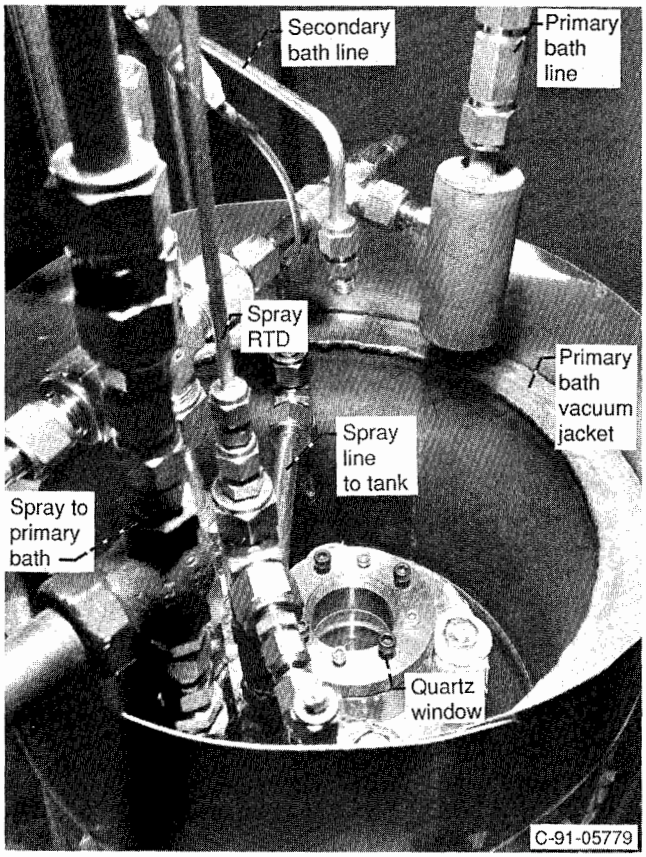
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TABLE 1.—FLAT SPRAY AND FULL CONE NOZZLE DATA

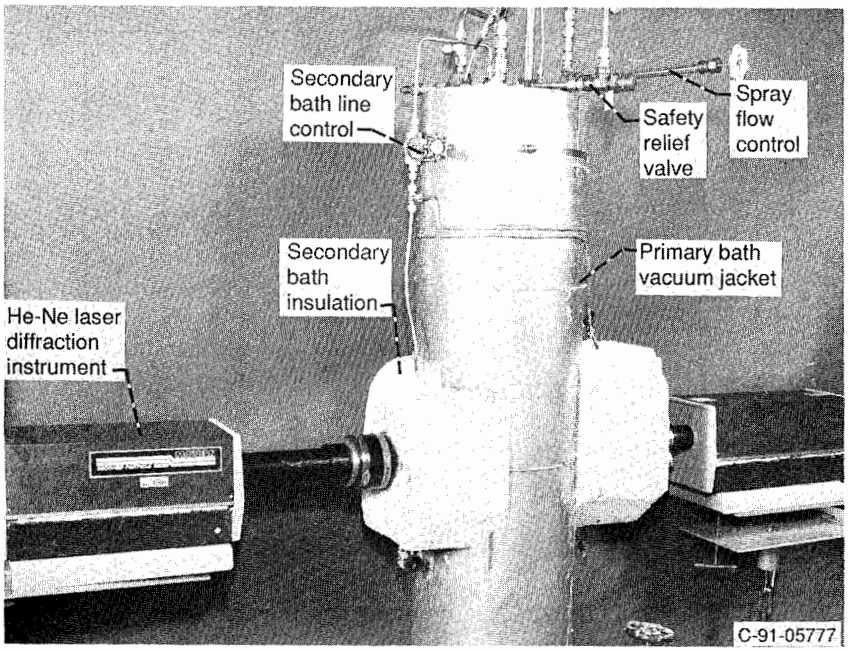
Nozzle[a] pressure, psia	Nozzle temperature, °R	Spray quality, percent	Laser obscuration, -	SMD[b] measured, μm	SMD calculated, μm
Flat spray					
17	139.6	0.32	0.46	250	265
18	139.6	.41	.83	205	237
19	139.8	.10	.94	208	217
20	139.6	0	.85	172	203
21	139.8	.57	.83	193	192
22	139.8	.55	.85	188	182
22	139.8	.56	.82	207	182
23	140.9	1.17	.83	177	174
25	140.4	.23	.86	186	162
25	140.9	.62	.96	172	162
27	140.6	.59	.86	157	152
27	140.9	1.16	.89	157	152
28	140.9	1.17	.93	159	148
30	140.9	1.19	.81	180	141
30	140.9	1.18	.90	168	141
30	141.2	1.32	.83	175	141
31	140.6	.55	.89	146	138
31	140.6	.55	.88	147	138
34	141.4	1.46	.91	124	130
34	140.4	.38	.77	118	130
35	140.4	.20	.99	101	128
35	141.4	1.50	.96	101	128
39	139.8	.13	.88	125	120
42	139.6	0	.94	107	115
45	139.8	.11	.92	93	111
Full cone					
20	139.3	.27	.91	197	143
20	139.6	.42	.94	190	143
21	139.8	.56	.84	121	124
22	140.1	.74	.99	83	110
22	139.8	.55	.91	97	110
24	140.1	.74	.99	81	90
25	139.8	.54	.97	76	83
25	140.6	1.03	.99	73	83
25	139.8	.56	.97	76	83
26	139.8	.55	.95	81	77
29	140.4	.84	.96	52	63
30	139.8	.55	.96	59	59
30	139.8	.54	.99	50	59
35	140.6	1.06	0.99	79	47

[a]Tank pressure at approximately 14.3 psia.

[b]SMD=Sauter Mean Diameter=$D_{32}=\frac{\sum_{i=1}^{m} V(x_i)}{\sum_{i=1}^{m} \frac{V(x_i)}{x_i}}$.



(a) Top view.



(b) Elevation view.

Figure 1.— Experimental tank configuration.

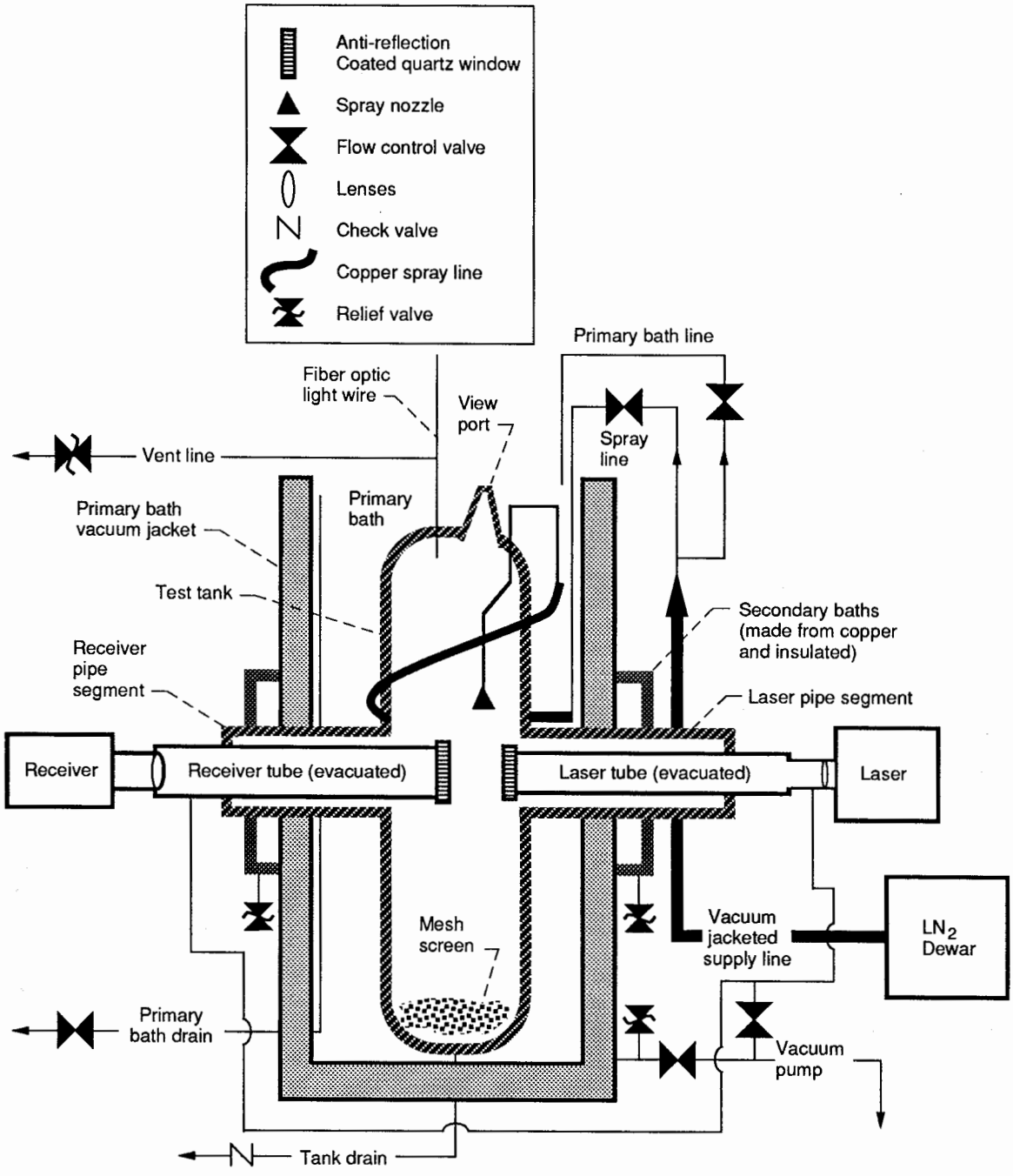


Figure 2.—LN_2 spray droplet measurement test flow system schematic.

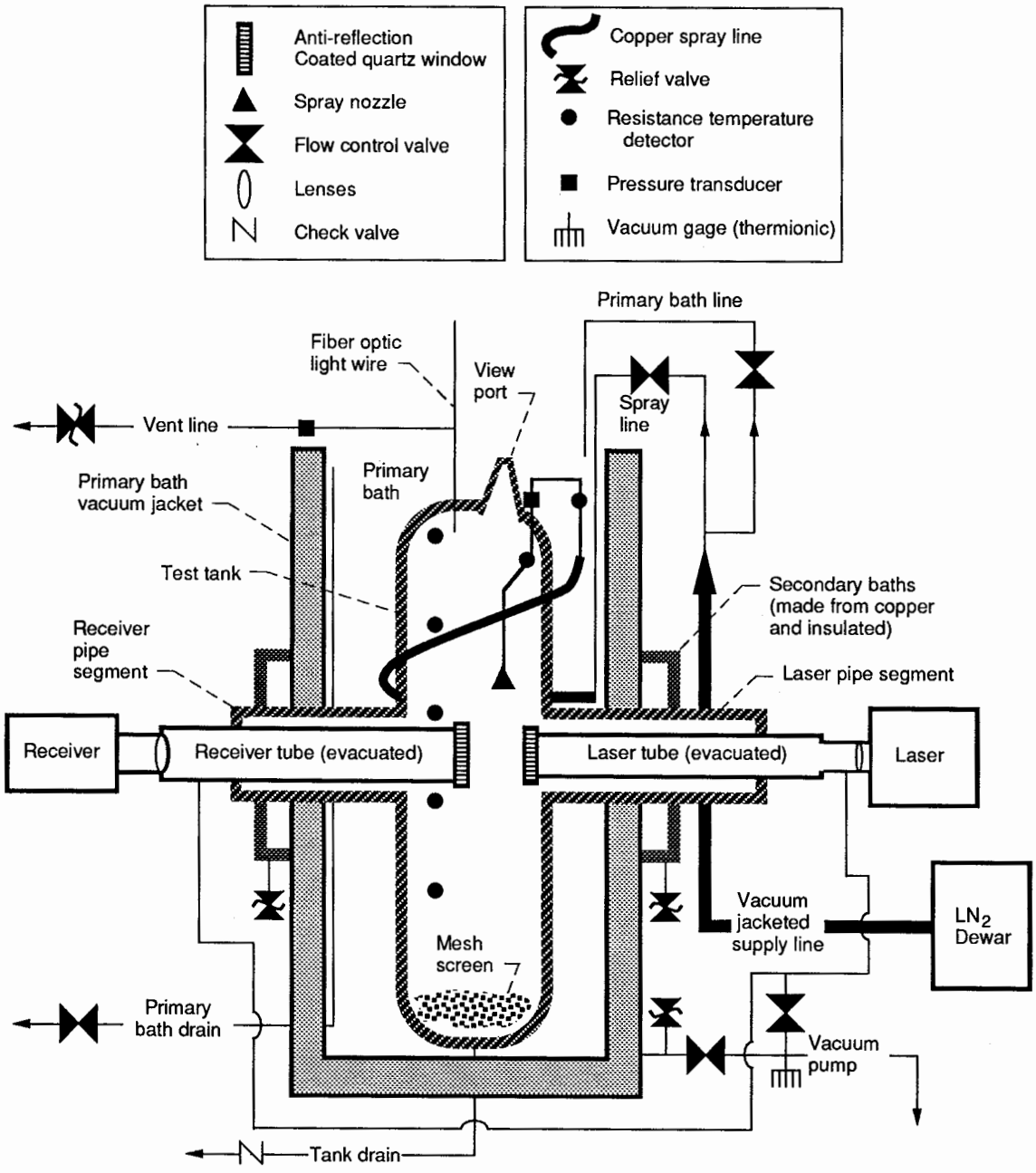
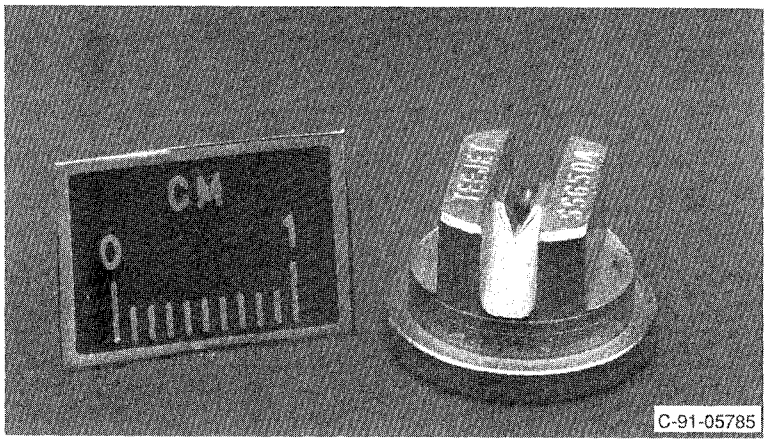
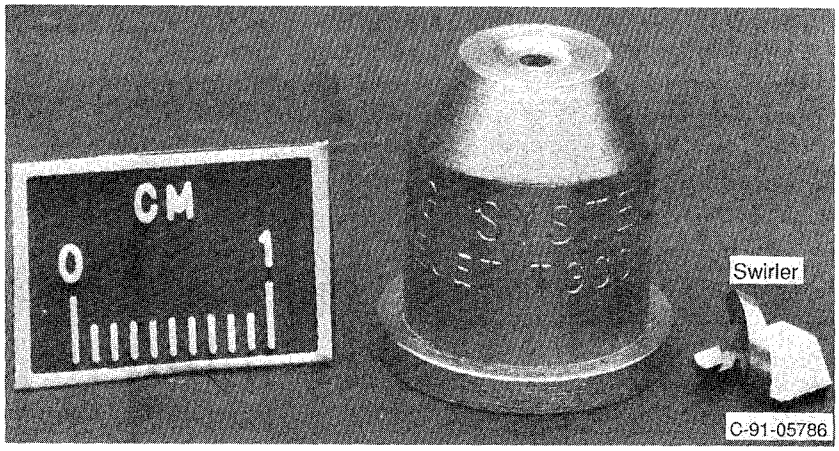


Figure 3.—LN_2 spray droplet measurement instrument schematic.

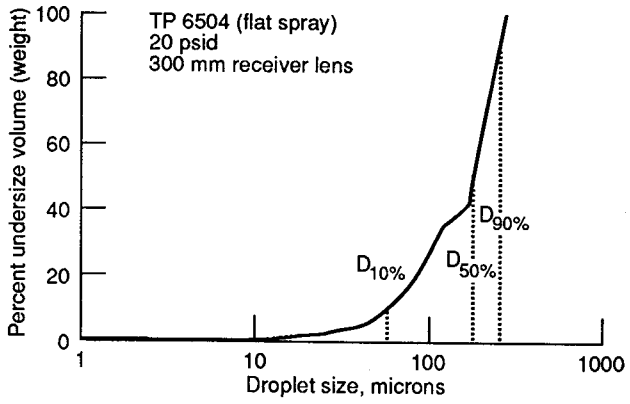


(a) TP-6504 Flat spray nozzle.

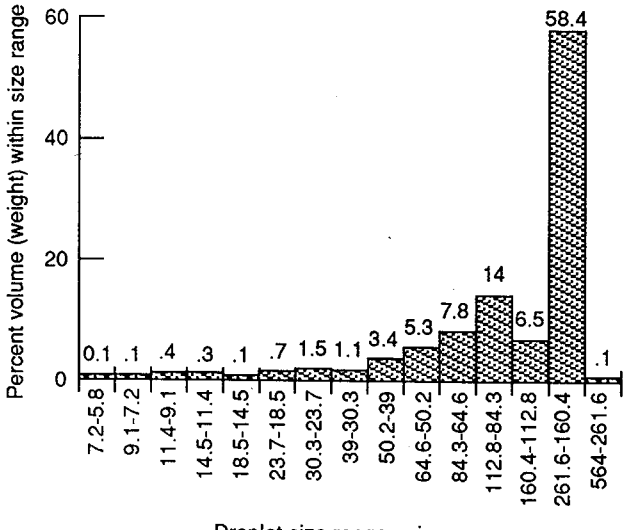


(b)TG-3 Full cone nozzle.

Figure 4.—Pressure atomizing nozzles tested.

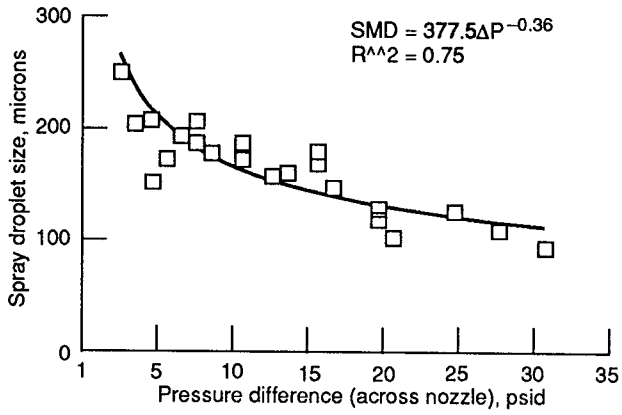


(a) Cumulative percent undersize volume (weight) distribution.

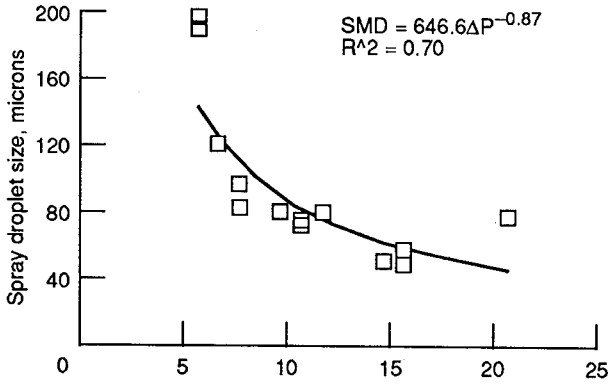


(b) Volume (weight) frequency distribution.

Figure 5.—Typical spray droplet size population information.



(a) Flat spray.



(b) Full cone.

Figure 6.—Pressure drop effect on SMD.

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16. Abstract

The size of subcooled liquified nitrogen droplets are measured with a 5 mW He-Ne laser as a function of pressure difference (ΔP) across flat spray and full cone pressure atomizing nozzles. For ΔP's of 3 to 30 psid the spray sauter mean diameter (SMD) ranged between 250 to 50 μm. The pressure range tested is representative of those expected during cryogenic fluid transfer operations in space. The droplet sizes from the flat spray nozzle were greater than those from the full cone nozzle. A power function of the form, $SMD \propto \Delta P^a$, described the spray SMD as a function of the ΔP very well. The values of 'a' were -0.36 for the flat spray and -0.87 for the full cone. The reduced dependence of the flat spray SMD on the ΔP was probably because of (1) the absence of a swirler that generates turbulence within the nozzle to enhance atomization, and (2) a possible increase in shearing stress resulting from the delayed atomization due to the absence of turbulence. The nitrogen quality, up to 1.5 percent based on isenthalpic expansion, did not have a distinct and measurable effect on the spray SMD. Both bi-modal and mono-modal droplet size population distributions were measured. In the bi-modal distribution the frequency of the first mode was much greater than the frequency of the second mode. Also, the frequency of the second mode was low enough such that a mono-modal approximation probably would give reasonable results.

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