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An Experimental Investigation of Thermal Absorption by Water Sprays

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FIRE RESEARCH & DEVELOPMENT GROUP

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ABSTRACT

This report describes the small-scale investigation of the thermal absorption of water sprays produced by a range of selected hydraulic nozzles against a propane fired radiant heat panel.

Measurements of thermal radiation attenuation have been made for six types of flat-fan water spray nozzles. Quantitative measurements of spray characteristics, including droplet size, have been undertaken and a method to examine the spray pattern distribution has been developed.

The results show that the most efficient thermal radiation attenuation is achieved with smaller droplets.

MANAGEMENT SUMMARY

INTRODUCTION

During operations, firefighters are often required to protect themselves and combustibles from the effects of radiant heat. The usual method of achieving this is to use a cooling water spray from a hosereel or mainline branch. The ability of water to absorb radiant heat has long been recognised and a number of small-scale theoretical studies have been conducted in recent years in an effort to provide a more quantitative understanding of this phenomenon. These studies have found that the thermal absorption capacity of a given spray is strongly correlated with droplet size and concentration.

There is a lack of experimental results in this area both in terms of small-scale and large-scale studies. The Fire Service would benefit from advice on what type of spray is most effective in reducing the effects of radiant heat. In order to achieve this there is a need to evaluate a range of sprays with different characteristics to determine which are the most effective. Initially a series of small-scale trials, using a range of spray-type nozzles and a radiant heat panel, have been carried out before larger scale tests could be considered using firefighting branches and a larger heat source.

THE TESTS

All the tests were carried out in the Heavy Equipment Laboratory at the Home Office's Fire Experimental Unit (FEU) in Moreton-in-Marsh. An experimental test rig was constructed which consisted of a propane fired radiant heat panel, water spray arrangement, flowmeter, pressure gauges, radiometer and a datalogger.

Various spray configurations were introduced between the radiant panel and the radiometer and the resulting thermal absorption, as measured by the radiometer, was recorded. A range of six different nozzles produced the sprays, which ranged from fine to coarse droplet sizes, and were operated at various flowrates. Water distribution patterns within the sprays were also investigated using a spray catching device. Information on droplet sizes was obtained using both a photographic method and high speed video image capturing system. The video image system also gave information on droplet speed and trajectory.

The first set of tests conducted were to determine the effect of a single spray. The various types of nozzles were operated over the pressure range (0 - 4 bar where possible) at 0.5 bar increments for periods of 30 seconds and then were turned off for 30 seconds. This allowed the radiation with no spray present to be recorded before the spray was operated at an increased flowrate.

The next step was then to investigate the effect of increasing the number of sprays between the radiant panel and the radiometer, thereby increasing the spray flux. The test procedure was:

- A single nozzle was mounted in the rig, the datalogger was started and recorded the radiant heat throughout the test. Pressure and flowrate were manually recorded.
- After a period of one minute the nozzle was operated for a period of one minute following which it was then turned off.
- After a further one minute, during which time a second nozzle (of the same type), was added to the arrangement behind the first, the sprays were then re-established.

- This sequence was then repeated for additional nozzles and then the entire test was then repeated for each of the different types of nozzle.

To examine the distribution of water within the spray patterns, a spray catching device was designed and built at the FEU. This consisted of a wooden, waterproof, semi-circular frame that was subdivided into 10 equal sections at 15° intervals. The frame was mounted on a stand and Silicone pipes led from each of the sections to a series of 10 collecting cans underneath the device. To determine the distribution patterns of the sprays, the catching device was positioned underneath the nozzle to be tested. The nozzle was then operated for a period of 5 minutes, at the settings given in the report. The water that subsequently collected in each of the collecting cans was then weighed using electronic scales and recorded manually.

MEASUREMENT OF DROPLET CHARACTERISTICS

A photographic method was developed in three stages to obtain data on droplet sizes:

- The first stage used a Nikon FE2 camera, a range of proprietary lenses and a conventional photographic flash gun. This was unsuccessful as the flash duration was unable to 'freeze' the droplets in flight and did not provide enough illumination. Also greater image magnification was needed to enable the images to be analysed.
- The second stage used the same camera and lenses as above but also a range of standard photographic extension tubes to increase the magnification available. A short duration light source specifically designed for the photography of high speed phenomena replaced the flash gun. Photographs of the droplets were taken using this method although it was found that greater magnification, than that obtained by the extension tubes, was required for the image analysis.
- The final stage used the Nikon FE2 camera, a purpose made extension tube fitted with a 600mm focal length lens and the short duration flash source. This method provided photographs of the droplets produced by all 6 types of nozzle.

Measuring the sizes of individual droplets from photographs was extremely time-consuming and tedious for the analyst. This was simply accomplished by comparing the droplets on the photographs with a millimetre scale on a rule. There is a question of the accuracy of the results from this method because of the measurement errors involved and thus the data that is obtained is of limited use. It is estimated that the measurement errors for this method range from ±60% for the smallest droplets to ±15% for the largest droplets.

The above methods were employed as a first step to gain an idea of the droplet sizes using equipment that was already available at the FEU. In order to gain more detailed measurements of both droplet size and speed, a high speed video capturing system and analysis package was required. A company who specialise in this type of work was identified and a contract was placed with them to provide the FEU with images of the droplets produced by the nozzles. The system uses a high speed video camera connected to a PC and twin flash gun arrangement. After a period of two days over 700 separate video images were acquired.

The analysis of the images obtained was performed by the FEU using a software package supplied by the company. This software enabled data on droplet size, speed and angle of trajectory to be obtained from the images. It is estimated that the measurement errors of droplet size for this method range from ± 4% for the best case, and ± 5% for the worst case.

A method to compare the spray flux and the thermal absorption results obtained was developed by the FEU. The method compares the cross-sectional area of the droplets within a 'standard' frame area to the amount of thermal absorption. This method is detailed and the results are given in the Appendices, however, because the sample size was too small the results are inconclusive. It was decided that to achieve a clearer picture of the droplet characteristics, far more time and effort would be needed to obtain considerable more data. This would enable a more accurate distribution of droplet sizes and thus an improved estimation of the spray flux to be attained.

RESULTS

Measurements of the thermal attenuation of single and multiple spray arrangements have been made. Examples of these results are given in the Figures.

The overall results of droplet characteristics from both measurement methods are given in the Figures and Tables within the report; more detailed results are given in the Appendices.

All the data recorded is available in Excel spreadsheet form.

CONCLUSIONS

It has been possible for some general conclusions from the work to be deduced:

- The results from the single nozzle tests show that for these types of nozzle, thermal attenuation is independent of flowrate.
- For multiple nozzle arrangements, thermal attenuation increases with spray flux.
- Smaller droplets are more efficient at reducing thermal radiation than larger droplets.
- In general, the largest droplets were produced by the AN40 nozzle and the smallest droplets were produced by the AN3 nozzle.
- The spray distribution patterns for each of the nozzles were shown to be relatively uniform within the main area of interest (sections 2-9 of the catching device).

It was hoped that the methods employed to obtain droplet data would provide useful information on the characteristics of the various sprays. Unfortunately there has been a learning process involved with this part of the project. It has identified the specialist knowledge and techniques that need to be applied to this area of the work, both of which were beyond the scope of this project, for meaningful results to be obtained.

FUTURE WORK

In order to determine the distributions of droplet sizes and characteristics produced by a nozzle significant time and effort needs to be employed for accurate results to be achieved. This is a highly specialised area of work and various techniques have been developed by other organisations to obtain this type of data. These would require further development if the techniques were to be applied to measurements on the sprays used by the Fire Service.

There is very little work on the thermal attenuation of sprays that has been carried out on a large-scale. In terms of practical advice to the Fire Service, larger scale tests using firefighting branches and a more suitable sized heat source could be developed and would be highly useful. Measurements of the thermal attenuation from branches that are actually used by the brigades to determine which are the most effective at reducing the effects of thermal radiation would be relatively straightforward to carry out.

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1 INTRODUCTION

During operations, firefighters are often required to protect themselves and combustibles from the effects of radiant heat. The usual method of reducing the effect is to use a cooling water spray from a hosereel or mainline branch.

The ability of water to absorb radiant heat has long been recognised and a number of small-scale theoretical studies have been conducted in recent years in an effort to provide a more quantitative understanding of this phenomenon (References 1-5). It has been found that the thermal absorption capacity of a given spray is strongly correlated with droplet size and concentration. There is a lack of experimental results in this area both in terms of small-scale and large-scale studies. Two studies have been identified (References 6-7) that considered the thermal absorption of sprinkler type sprays and only one study (Reference 8) details full-scale trials using fire service branches.

Branches are operated by the fire service at a variety of flowrates with hosereel branches used at up to 150 lpm and mainline branches used at up to 1100 lpm. The fire service would benefit from advice on what type of spray is most effective in reducing the effect of radiant heat. To achieve this there is a need to evaluate a range of sprays with different characteristics to determine which are the most effective. Initially a series of small-scale trials, using a range of spray-type nozzles and a radiant heat panel, have been carried out before larger scale tests could be considered using firefighting branches and a larger heat source.

An experimental test rig was constructed with a propane fired radiant heat panel separated by several metres from a radiometer. Various spray configurations were introduced between them and the resulting thermal absorption, as measured by the radiometer, was recorded. The sprays ranged from fine to coarse droplet sizes and were operated at various flowrates. Water distribution patterns within the sprays were also investigated using a spray catching device, and both a photographic method and high speed video image capturing system were used to give information on droplet sizes. The video image system also gave information on droplet speed and trajectory.

2 DESCRIPTION OF EQUIPMENT USED AND EXPERIMENTAL METHODS

2.1 General

All the tests were carried out in the Heavy Equipment Laboratory at the Home Office's Fire Experimental Unit (FEU) in Moreton-in-Marsh. The test rig consisted of a propane fired radiant heat panel, the water spray arrangement under test, flowmeter, pressure gauges, radiometer and datalogger. A spray catching device to determine water distribution within the spray was used and photographs of the sprays to determine droplet sizes were taken. A video imaging capturing system was also employed to give more detailed and accurate droplet characteristics.

2.2 Radiant Panel

The FEU had purchased a radiant heat panel for a previous project but this had never been commissioned. A system[1] (Superscripts refer to Notes on page 12) to operate the panel was specified, ordered and delivered which consisted of the radiant panel, a gas burner system, semi-automatic flame failure unit, air blower, associated pipework and a mounting/enclosure for the complete unit. The radiant panel itself was 0.30m x 0.30m square, mounted vertically, and was fuelled by a premixed propane gas and air supply (Figure 1).

2.3 Hydraulic Arrangement

The hydraulic arrangement for the tests consisted of a 150 litre water tank, gear pump[2], electromagnetic flowmeter[3], manifold, pressure gauges, supply pipework to each nozzle, and a mounting frame (Figure 2). The nozzles were aligned along the central axis of the radiant heat panel, such that the sprays operated parallel to its face.

Various nozzles[4] (Figure 3) were purchased for the trials to cover a range of flowrates and droplet sizes. The manufacturer does not state droplet sizes although, in general, the AN40 nozzle was expected to produce the coarsest droplets and the AN3 nozzle to produce the finest droplets. The nozzles could be operated over a range of pressures; the upper limit for these tests was determined by the limitations of the gear pump. Examples of the nozzle details, as well as operating pressures and flowrates used in the tests are given in the table below:

Nozzle	Orifice Diameter* mm	Type	Fan Angle*	Pressure (Bar)	Flow (lpm)
AN 40	5.3	Flat fan	145°	0.5	11.1
AN 20	3.8	Flat fan	145°	1.0	8.6
AN 10	2.6	Flat fan	145°	2.0	6.2
AN 7.5	2.3	Flat fan	145°	2.0	4.9
AN 5.0	1.9	Flat fan	125°	3.0	4.2
AN 3.0	1.4	Flat fan	125°	4.0	2.8

*Manufacturers data

Table 1 : Nozzle Details

During the tests the nozzles were positioned at a height of 1.39m from the floor and orientated to give a vertical spray downwards. This height was used to ensure that the spray pattern completely obscured the view of the radiant heat source from the radiometer. When a single nozzle was used it was mounted at a distance of 1.00m from the face of the radiant panel. When more than a single nozzle was used, the nozzles were mounted at distances of 1.00m, 1.14m, 1.28m, and 1.42m from the face of the radiant panel. These distances were used to ensure that the sprays from the nozzles did not impinge on the radiant panel surface or the radiometer face and that the sprays from each nozzle did not interfere with one another.

Each nozzle was connected to a pressure gauge to enable the pressure at the inlet of the nozzle to be measured. The total flow through the nozzle arrangement (i.e. when 1, 2, 3 or 4 nozzles were used together) was measured using an electromagnetic flowmeter with a digital display panel mounted on a trolley (Figure 4).

2.4 Radiometer

Thermal radiation measurements were made using a calibrated Medtherm Instruments 64-Series Schmidt-Boelter type heat flux meter[5] (Figure 5). This was positioned 1.50m from the panel surface at a height of 1.18m above the floor (centre height of the radiant panel). To enable the radiometer's heat sink to be kept at a constant temperature, the radiometer was cooled throughout the tests by circulating cold water by means of a pump and hoses connected to a tank.

2.5 Datalogger

The output of the radiometer was recorded every second to the floppy disc drive of a Solartron Scorpio datalogger[6] (Figure 6). The data were then replayed using a computer and Scorpio software to enable the data to be processed at a later date using an Excel spreadsheet.

2.6 Initial Tests

Three preliminary tests were undertaken to determine the warm-up time and thermal characteristics of the panel. The datalogger was started logging and recorded the radiometer output every second to the floppy disc drive of the logger. The datalogger was also set-up to display the heat flux in kW/m^2 on its screen. The panel was then ignited and allowed to operate until such time as the heat output of the panel appeared to have stabilised as indicated on the datalogger screen.

In Test 1, the heat flux was measured at 1m from the panel surface and level with the centre of the panel (1.18m from the floor). Heat flux was measured at the bottom of the panel (1.03m from the floor) in Test 2 and at the top of the panel (1.33mm from the floor) in Test 3 . A hand held digital thermometer and K-type probe was also used to measure the operating temperature of the surface of the panel.

The results from these tests were;

- A stabilised heat output from the panel was obtained after 20 minutes from ignition

- The panel operated at a surface temperature of 950 °C
- The maximum heat flux was measured with the radiometer mounted so that it was looking at the centre of the panel (as in Test 1). This position was used for the tests.

2.7 Measurement of the Thermal Absorption of Single Nozzle Water Sprays at Various Flowrates

The following procedure was used to measure the thermal absorption of a single nozzle:

1. A single nozzle was mounted 1.00m from the surface of the panel at a height of 1.39m from the floor.
2. The radiant panel was allowed to warm-up for 20 minutes at the end of which the datalogger was started.
3. The thermal radiation was recorded from 1 minute prior to the spray being operated.
4. The various nozzles were operated over the pressure range (0 - 4 bar where possible) at 0.5 bar increments for periods of 30 seconds and then were turned off for 30 seconds. This allowed the radiation with no spray present to be recorded before the spray was operated at an increased flowrate. Pressure and flowrate were recorded manually at each 0.5 bar increment except for the AN40 which was operated at intervals of 0.25 bar for this series of tests.

It was only possible to operate the AN20 nozzle to a maximum of 3.5 bar (16 lpm) and the AN40 nozzle to a maximum of 1.25 bar (18.2 lpm) due to the limitations of the gear pump.

2.8 Measurement of the Thermal Absorption of Multiple Nozzle Water Sprays

The next phase was to investigate the effect of increasing the number of sprays between the radiant panel and the radiometer, thereby increasing the spray flux. The test procedure was:

1. The radiant panel was allowed to warm-up for a period of 20 minutes prior to the trial. A single nozzle was then mounted in the rig at a distance of 1.00m from the surface of the panel at a height of 1.39m from the floor.
2. The datalogger was started and recorded the radiant heat throughout the test. Pressure and flow were manually recorded.
3. After a period of one minute the nozzle was operated for a period of one minute and then it was turned off.
4. After a further one minute, in which time a second nozzle (of the same type) was added to the arrangement the sprays were then re-established.
5. This sequence was then repeated for additional nozzles and then the entire test was then repeated for each of the different types of nozzle.

2.9 Measurement of the Spray Pattern

To examine the distribution of water within the spray patterns, a spray catching device (Figure 7) was designed and built at the FEU. It consisted of a wooden, waterproof, semi-circular frame that was subdivided into 10 equal sections at 15° intervals (150° total catching angle). The frame was mounted on a Dexion stand 0.30m below the nozzle. Silicone pipes led from each of the sections to a series of 10 collecting cans underneath the device.

To determine the distribution patterns of the sprays, the catching device was positioned underneath the nozzle to be tested. The nozzle was then operated for a period of 5 minutes, which was timed using a digital stopwatch, at the settings given in Table 1. The water that subsequently collected in each of the collecting cans was then weighed using electronic scales and recorded manually. Each of the 6 types of nozzle was tested twice to obtain an average value.

2.10 Methods to Investigate Droplet Size and Characteristics

2.10.1 Still Photography

The method to photograph the droplets was developed in three separate stages:

1. The initial method used a Nikon FE2 camera, a range of proprietary lenses and a conventional photographic flash gun. This method proved unsuccessful as the images obtained were both blurred and too dark. This was due to the flash duration not being fast enough to 'freeze' the droplets in flight and the output not providing enough illumination. It was also decided that greater image magnification was required to make the analysis of the photographs possible.

2. The second stage used the same camera and lenses as above but also a series of standard photographic extension tubes to increase magnification. A Pulse Argon Stabilised Spark Gap[7] was also used which is a short duration light source specifically designed for the photography of rapid moving phenomena (Figure 8). This provided a single flash of 1 microsecond duration which was synchronised with the camera shutter by connecting a suitable cable. Several films were exposed in tests to determine the best camera settings for the photographs and to explore whether it was better to back-light or front-light the sprays. The tests proved it was best to back-light the spray to produce a shadowgraph of the droplets. Although photographs were taken using this method a greater magnification was required for image analysis than could be achieved with photographic extension tubes.

3. The final stage used the Nikon FE2 camera fitted with a 4.20m purpose made extension tube and a 600mm focal length lens to increase the magnification. The spark gap device was also used and a databack was also fitted to the camera to help with the identification of the prints. The whole arrangement was mounted on 'V' blocks on a bench because of its length and weight and to ensure that the set-up was stable. To aid

with focusing a ruler was placed in the centre of the spray area and the camera was focused on this. This ensured that the images would be taken from the main area of interest in the centre of the spray and provided a reference scale for use in the image analysis. Initially the first few frames were taken of the focused ruler for reference (with no spray established) this was then removed and the spray then established. All of the photographs of each of the six sprays were taken at the spray settings as detailed in Table 1.

The above methods were employed as a first step to gain an idea of the droplet sizes using equipment that was already available at the FEU. Some measurements were made although there is a question of the accuracy of the results gained by these methods due to the measurement errors involved (see section 4.3).

2.10.2 High speed video image capturing system

In order to gain more detailed measurements of both droplet size and speed a high speed video capturing system and analysis package was used. A company who specialise in this type of work was identified and a contract was placed with them to provide the FEU with images of the droplets produced by the nozzles. Over 700 separate video images were acquired after operating the system over a period of two days.

The system uses a high speed video camera[8] connected to a PC and a multiple short duration, twin-flash gun arrangement (Figure 9). Various shutter speeds and flash delay times were set on the camera to capture the best image. Both double-flash and triple-flash images were taken to give information on droplet speed and if required, acceleration. In addition, different lenses were also fitted to the camera in order to increase or decrease the field of view of the system. The video camera and flash guns were positioned in front of the spray at a height of 1.18m from the floor which was the same height as the radiometer and therefore was looking at the equivalent view through the spray. A copper plate was positioned behind the spray which reflected the light from the flash guns. This was a technique that the contractor had developed to improve the images as the droplets would appear as a shadowgraph. A ruler was also placed in the centre of the spray to aid focusing. This ensured that the images would be taken from the main area of interest of the spray and, provided a reference scale for use in the image analysis. As detailed in the photographic method, the first image of each of these series was of only the ruler for reference (i.e. no spray). This was then removed, the spray established and images of the droplets were obtained.

The images were taken with the nozzles operating at the settings in Table 1. Several series of images were taken of each spray with various fields of view. This was done in order that the various sizes of droplets within the spray could be accommodated within the view, i.e. a wider view to concentrate on larger droplets and a narrower view for the smaller droplets.

The analysis of the images acquired was performed by the FEU using a software package supplied by the company. This software enabled data on droplet size, speed and angle of trajectory to be obtained from the images for further analysis using Excel spreadsheets. This was a time consuming and tedious task but was the only way to process the data.

Discussions were held at the FEU to determine the most appropriate way to interpret the droplet data obtained. A method to compare the spray flux produced by the 6 types of nozzles and the thermal absorption results obtained was developed. The method compared the cross sectional area of the droplets within a 'standard' frame area to the amount of thermal absorption. This method is detailed and results are given in Appendix A, however the results are inconclusive mainly due to the sample size being too small and the other reasons given later in section 4.4.

3 RESULTS

Figure 10 shows an example of the thermal attenuation results from a single nozzle test and shows that attenuation does not increase with flow. Column 4 of Table 2 below details the results from all of the single nozzle tests. Figure 11 shows an example of the results from one of the multiple nozzle tests and Figure 12 compares the results of all the multiple nozzle arrangements for each nozzle type.

Figure 13 was produced using regression analysis from Figure 12 and the gradient of this graph indicates the efficiency of each nozzle. The greater the gradient the more efficient the nozzle. The total flow plotted represents a single spray which may comprise of up to four separate sprays and assumes the droplet sizes are homogenous for each nozzle type. It can clearly be seen from this graph that the most efficient nozzle was the AN3 which had a value of 1.69 percent/litre. By comparison the least efficient, the AN40 nozzle, had a value of 0.85 percent/litre.

An example of the results from a spray distribution tests is given in Figure 14. The results show segments 2 to 9 are evenly distributed and segments 1 and 10 generally contain the largest amount of water. Similar results were obtained for all the different types of nozzles.

The summary results from both the photographic and high speed video methods are presented in Table 2 below and histograms[9] of the droplets for each nozzle are given in Appendix A (High speed video) and Appendix B (photographic). Appendix A also gives detailed results from the video system. Figure 15 shows an example of one of the photographs of the droplets and Figure 16 shows an example of one of the double-flash high speed video images.

Figure 17 shows the differences of the average sizes and standard deviations from both measurement methods.

Figure 18 shows the thermal attenuation achieved at a nominal 25 lpm against droplet diameter, including standard deviations, for each type of nozzle. This shows that smaller droplets are more efficient than larger droplets at reducing thermal radiation.

				Photographic method			High speed video method				
Nozzle	Flow Lpm	Pressure Bar	Thermal Attenuation %	Average diameter Microns	Std Dev	No. of drops measured	Average diameter Microns	Std Dev	Average Speed m/s	Std Dev	No. of drops measured
AN40	11.1	0.5	11	289	189	27	547	247	7.68	1.15	188
AN20	8.6	1	9	160	142	73	360	194	10.81	1.67	259
AN10	6.2	2	9	95	88	148	275	164	13.00	3.77	42
AN7.5	4.9	2	8	73	68	230	109	92	5.78	4.02	55
AN5	4.2	3	7	65	51	223	100	97	5.19	4.12	44
AN3	2.8	4	5	65	52	350	99	45	5.43	4.46	43

Table 2: Thermal Attenuation Results for Single Nozzle Tests and Droplet Details

4 DISCUSSION OF RESULTS

4.1 Thermal Absorption Results

Initially a single nozzle of each type was operated at 0.5 bar increments up to 4 bar where possible. The results from the six nozzles show that increasing the operating pressure of the nozzle and consequently the flowrate, does not increase the thermal attenuation of these types of spray. This would suggest that although the actual flowrate through the nozzle increases, the spray flux (mass of water per unit volume) does not increase. It would be expected that the speed of the droplets would increase but it has not been possible, in the time available, to investigate this further. This would involve collecting much more data using the video capturing system.

The single nozzle that achieved the greatest attenuation (11%) was the AN40. This produced the largest droplets of the range of nozzles, and had the largest flowrate

The results from the AN20, AN10 and AN7.5 nozzles are similar and show that when a single nozzle was used all three achieved an attenuation of 8-9%. However the AN7.5 achieved this with a flowrate of 4.9 lpm, the AN10 nozzle with a flowrate of 6.2 lpm and the AN20 had a flowrate of 8.6 lpm. The results also show that, for multiple nozzle arrangements, the AN7.5 nozzle achieved attenuation figures within 3% of those of the larger AN20 nozzle but only used approximately just over half of the flowrate.

Figure 18 combines the results from the thermal attenuation tests and the measurement of droplet sizes from the video method. The accuracy's of the results are indicated using the calculated standard deviations. A power equation trendline[10] has been fitted to the data using the least squares fit through the points. The graph shows that, for a constant flowrate of a nominal 25 lpm, the thermal attenuation achieved increases as droplet size decreases and therefore, that smaller droplets are more efficient than larger droplets at reducing the effects of thermal radiation.

4.2 Spray Pattern Distribution

The results from the spray distribution patterns for each of the nozzles show the distribution in segments 2-9 is relatively evenly distributed. The results also show that segments 1 & 10 generally contain the largest amount of water. This 'spray-edge' effect can be ignored because these segments are outside the main area of interest. This exercise was done to confirm that the "curtain" of spray between the radiometer and the radiant panel was relatively consistent throughout its length i.e. that no 'fingering' effects occurred. Adjustments have been made for the edge effect in the calculations detailed in Appendix A.

4.3 Droplet Sizes from the Photographic Method

Measuring the sizes of individual droplets from photographs is extremely time-consuming and tedious for the analyst. This is simply accomplished by comparing the droplets on the photographs with a millimetre scale on a rule. Because it is difficult to measure better than to ½mm by eye, the measurements could have inaccuracies of up to 100% for the smallest droplets. Those droplets that are smaller than ½mm on the photographs cannot be measured. The measurements taken from the photographs are only estimated to be accurate to ± 40 microns because of the magnification and measurement errors involved. Therefore the results, particularly from the smaller droplets, are of limited value.

For droplet size to be established reliably, it is desirable to study as many photographs as possible. This is to ensure that a representative sample of the droplets in the spray have been captured and to allow the measurement of as many droplets as possible.

The photographs show that, in general, the largest droplets are produced by the AN40 type nozzle and the smallest drops are those produced by the AN3 nozzle.

4.4 Results from the High Speed Video System

The high speed video system produced the more accurate measurements of droplet sizes, and enabled the speed and angle of trajectory to be determined. However, the results themselves are far from conclusive and after the analysis was completed, it was concluded that many more measurements were required to achieve a clearer picture of the droplet characteristics. This would enable a more accurate distribution of droplet sizes, and thus an improved estimation of the spray flux, to be attained. The sample of droplets that were able to be measured was too small for any real conclusions to be drawn from the data that was analysed.

4.5 Comparison of Measurement Methods and Estimation of Errors

Of the two methods the video system is considered to be the more accurate; this is mainly because the analysis software could be calibrated and measurement errors were smaller. Also the field of view of this method could be adapted from a narrow view, to obtain images of the smaller droplets, and increased to a wider view for the larger droplets. There are large differences in the values of droplet sizes between the two methods for the AN40, AN20 and AN10 nozzles. This is mainly due to the fact that very few large droplets were measured from the photographic method. The photographs do show evidence of large droplets but these are not always in focus or only appear as part images and only complete in focus drops were measured. One of the problems that hinders the photographic method is that it has a fixed field of view. When used to photograph the largest droplets this was too narrow and, when used to photograph the smallest droplets, was too wide. This meant that large droplets could appear as only part of an image and that the smaller droplets appeared too small to be measured. It was not possible in the time available to overcome this with the equipment available at the FEU.

Estimations of the errors associated with both methods of droplet size measurement have been made. In the photographic method the measurements are only accurate to within ± 40 microns, which equates to errors ranging from ± 60% for the smallest drops, down to ± 15% for the largest drops. There is a large standard deviation associated with the measurements due to the relatively small sample size and the variation in the size of the droplets produced by each spray.

In the case of the video system, the errors are of the order of ± 20 microns (± 4%) which is the best case, and ± 5 microns (± 5%) in the worst case. Again, as in the photographic method there is a large standard deviation associated with the measurements for the same reasons as detailed above.

5 CONCLUSIONS

It has been possible for some general conclusions from the work to be deduced:

- The results from the single nozzle tests show that for these types of nozzle, thermal attenuation is independent of flowrate.
- For multiple nozzle arrangements, thermal attenuation increases with spray flux.
- Smaller droplets are more efficient at reducing thermal radiation than larger droplets.
- In general, the largest droplets were produced by the AN40 nozzle and the smallest droplets were produced by the AN3 nozzle.
- The spray distribution patterns for each of the nozzles were shown to be relatively uniform within the main area of interest (sections 2-9 of the catching device).

It was hoped that the methods employed to obtain droplet data would provide useful information on the characteristics of the various sprays. The high speed video method was the most promising but the results were limited by the relatively small number of measurements made. The work has identified that specialist knowledge and techniques need to be applied to this area of the work and significant time devoted to droplet analysis, both of which were beyond the scope of this project.

6 FUTURE WORK

In order to determine the distributions of droplet sizes and characteristics produced by a nozzle significant time and effort needs to be employed for accurate results to be achieved. This is a highly specialised area of work and various techniques have been developed by other organisations to obtain this type of data. These would require further development if the techniques were to be applied to measurements on the sprays used by the Fire Service.

There is very little work on the thermal attenuation of sprays that has been carried out on a large-scale. In terms of practical advice to the Fire Service, larger scale tests using firefighting branches and a more suitable sized heat source could be developed and would be highly useful. Measurements of the thermal attenuation from branches that are actually used by the brigades to determine the most effective at reducing the effects of thermal radiation would be relatively straightforward to carry out. Investigation of the droplet characteristics would be much more difficult and involve significant development of techniques for recording and analysis.

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3. Coppalle, A. Nedelka, D. & Bauer, B. Fire Protection: Water Curtains, Fire Safety Journal, 20, pp241-255, 1993.

4. Buchlin, J.M, & Pretrel, H. Atténuation de Sources Thermiques Radiatives par Ridaux d'Eau, European Commission, Industrial Fires II : Workshop Proceedings, 17-18th May 1994, Cadarache, France.

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6. Murrell, J.V, Crowhurst, D & Rock, P. Experimental Study of the Thermal Radiation Attenuation of Sprays from Selected Hydraulic Nozzles, Halon Options Technical Working Conference : Proceedings, 9-11th May, 1995, Albuquerque, NM.

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NOTES

1. Radiant heat panel control system produced by Trueflame. 5 Judge Court, North Bank, Berry Hill Industrial Estate, Droitwich, Worcestershire, WR9 9AU.

2. Electromotors Ltd gear pump, Model MD112130

3. ABB Kent-Taylor Magmaster 15mm flowmeter. ABB Kent-Taylor Ltd, Howard Road, Eaton Socon, St. Neots, Huntington, Cambridgeshire, PE19 3EU

4. Lurmark AN40, AN20, AN10, AN7.5, AN5 and AN3 nozzles. Lurmark Ltd, Station Road, Longstanton, Cambridge, CB4 5DS.

5. Medtherm Corporation 64-1-20-K series heat flux transducer. Paar Scientific Ltd, 594 Kingston Road, Raynes Park, London, SW20.

6. Solartron Instruments SI3535D Scorpio Data Logger. Solartron Instruments, Victoria Road, Farnborough, Hampshire. GU14 7PW.

7. Pulse Argon Jet Stabilised Spark Gap. Pulse Photonics Ltd, Shepherds Road, Bartley, Southampton, SO4 2LH.

8. Electronic High Speed Imaging. Pulse Photonics Ltd, Shepherds Road, Bartley, Southampton, SO4 2LH.

9. Histograms produced using 'Histogram' data analysis tool in Microsoft Excel

10. Power equation trendline produced using 'Trendline' data analysis tool in Microsoft Excel

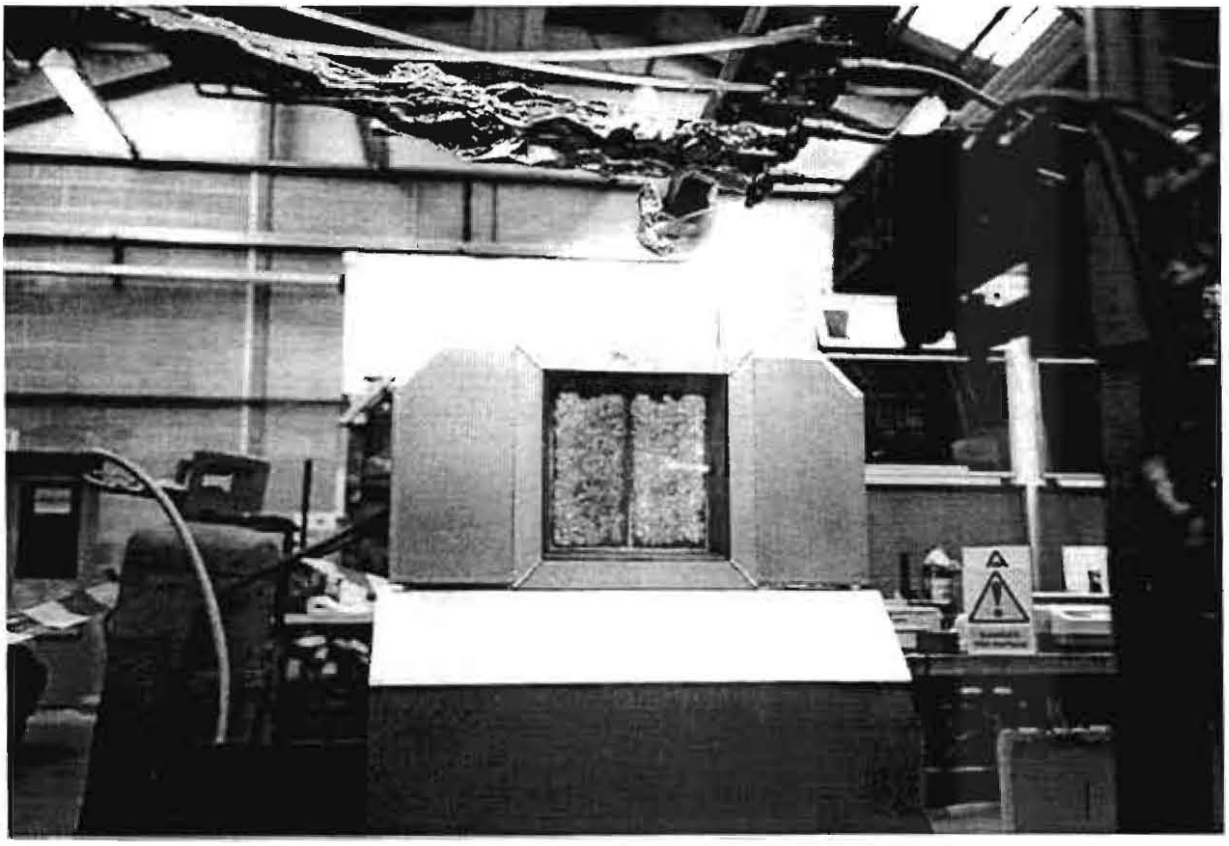

Figure 1 : Radiant panel

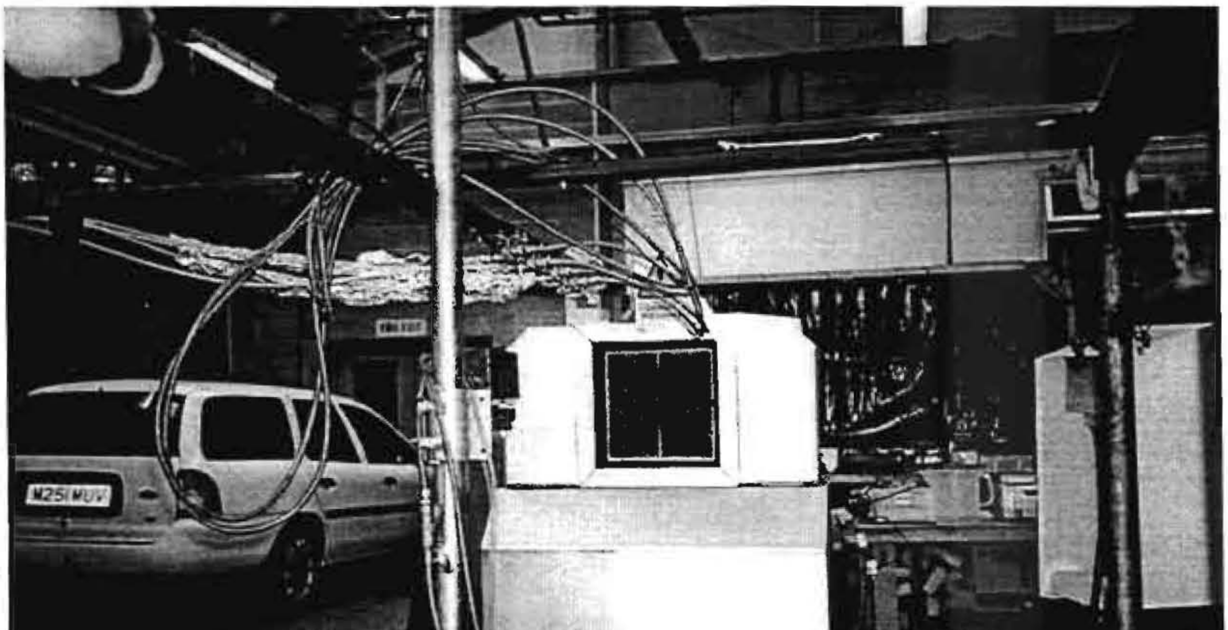

Figure 2: Nozzle arrangement

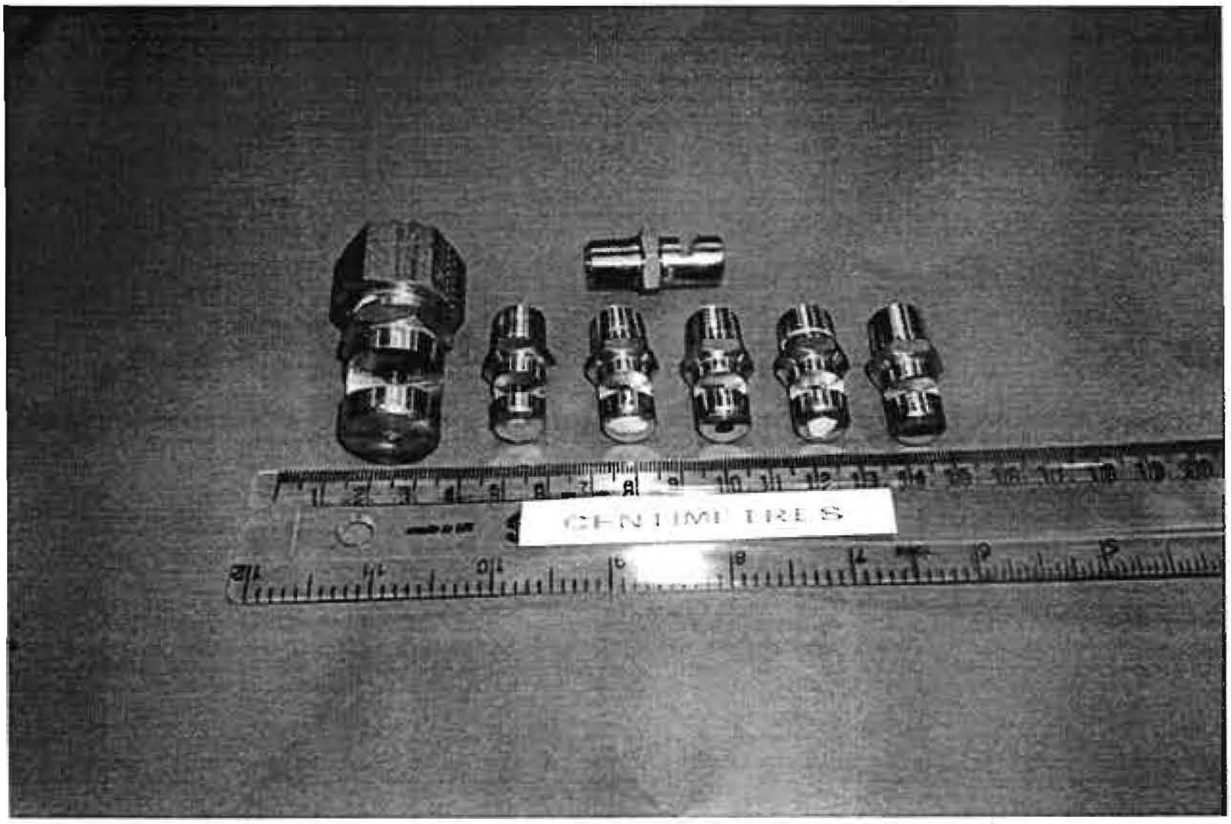

Figure 3: Spray nozzles

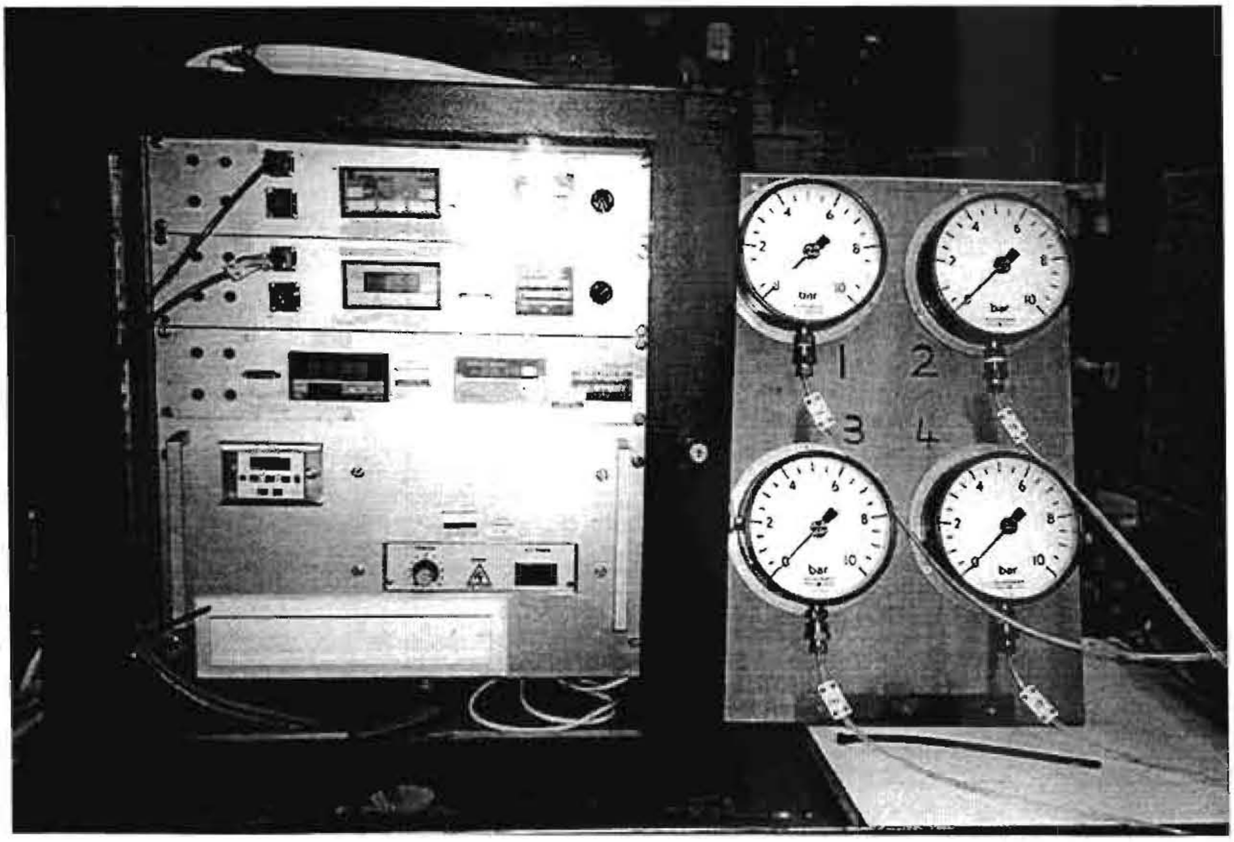

Figure 4: Pressure gauges and flowmeter readout

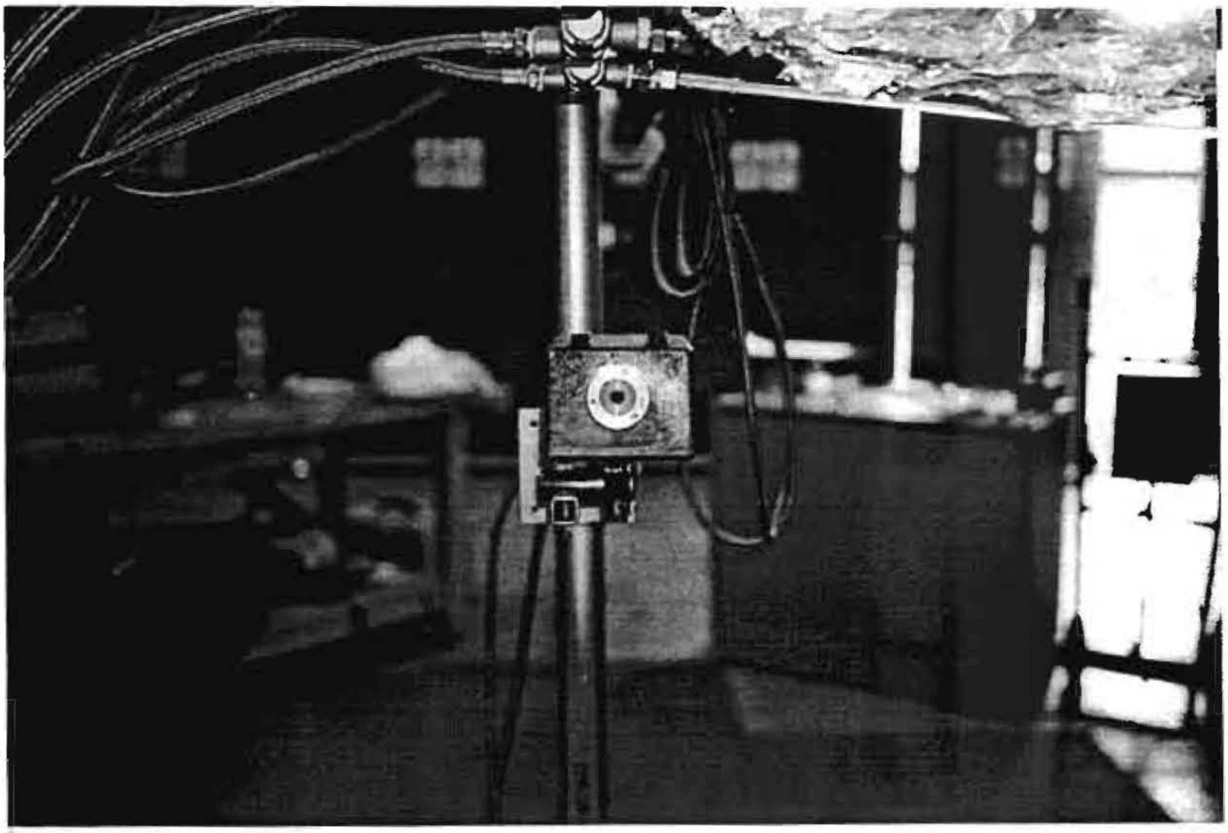

Figure 5 : Radiometer

Figure 6: Scorpio datalogger

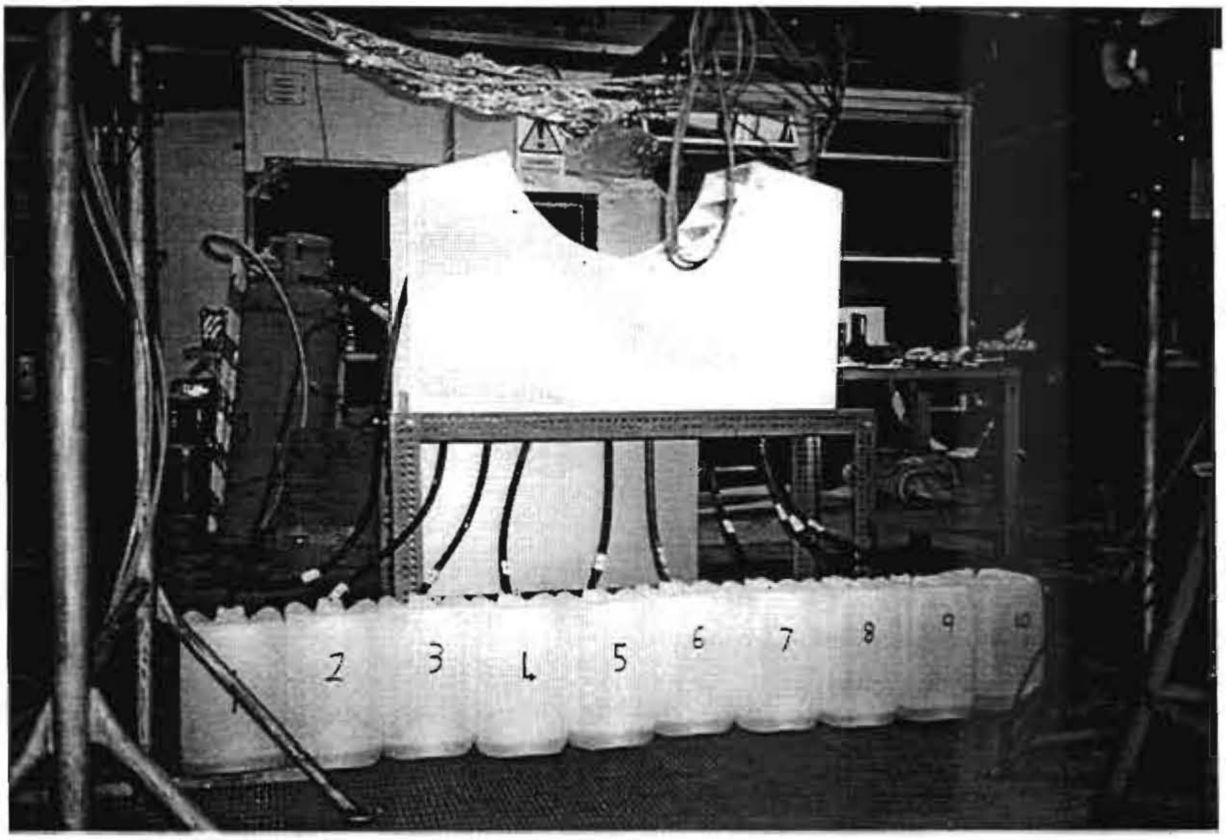

Figure 7: Spray catching device

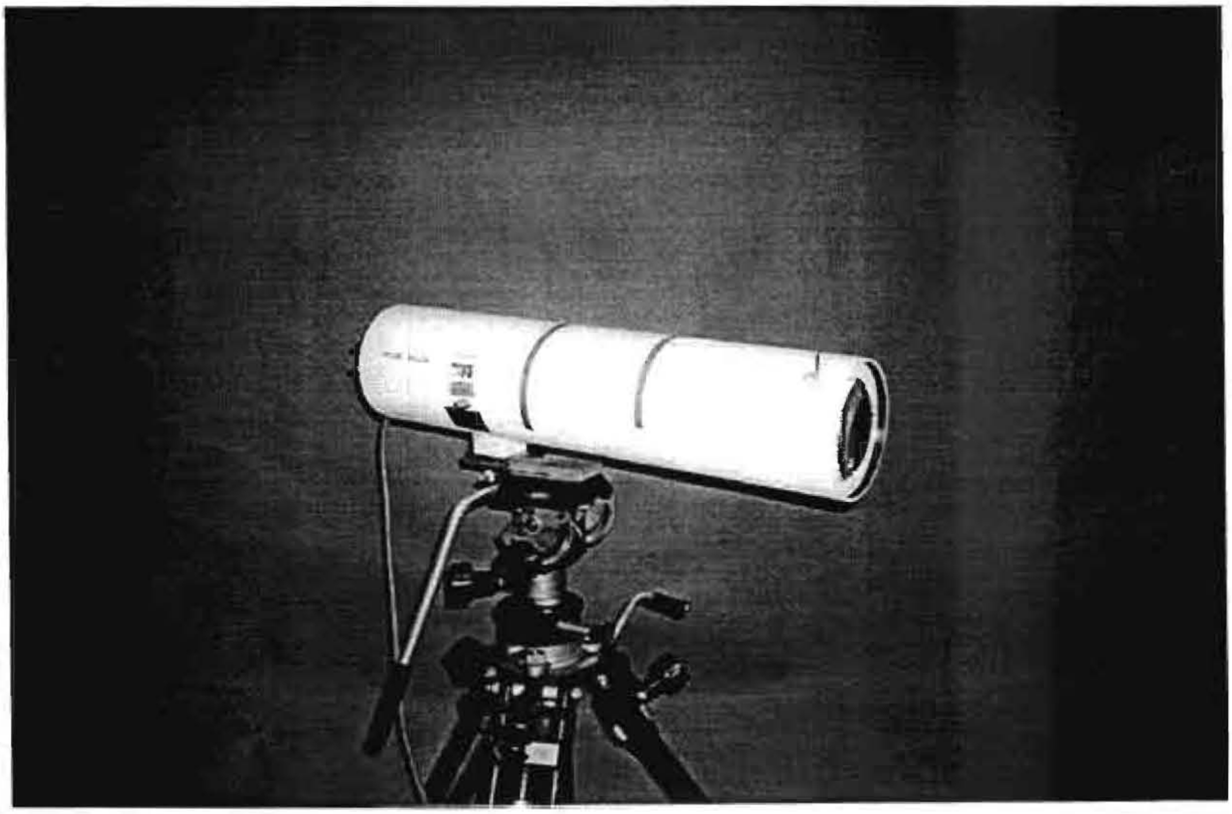

Figure 8: Spark gap device

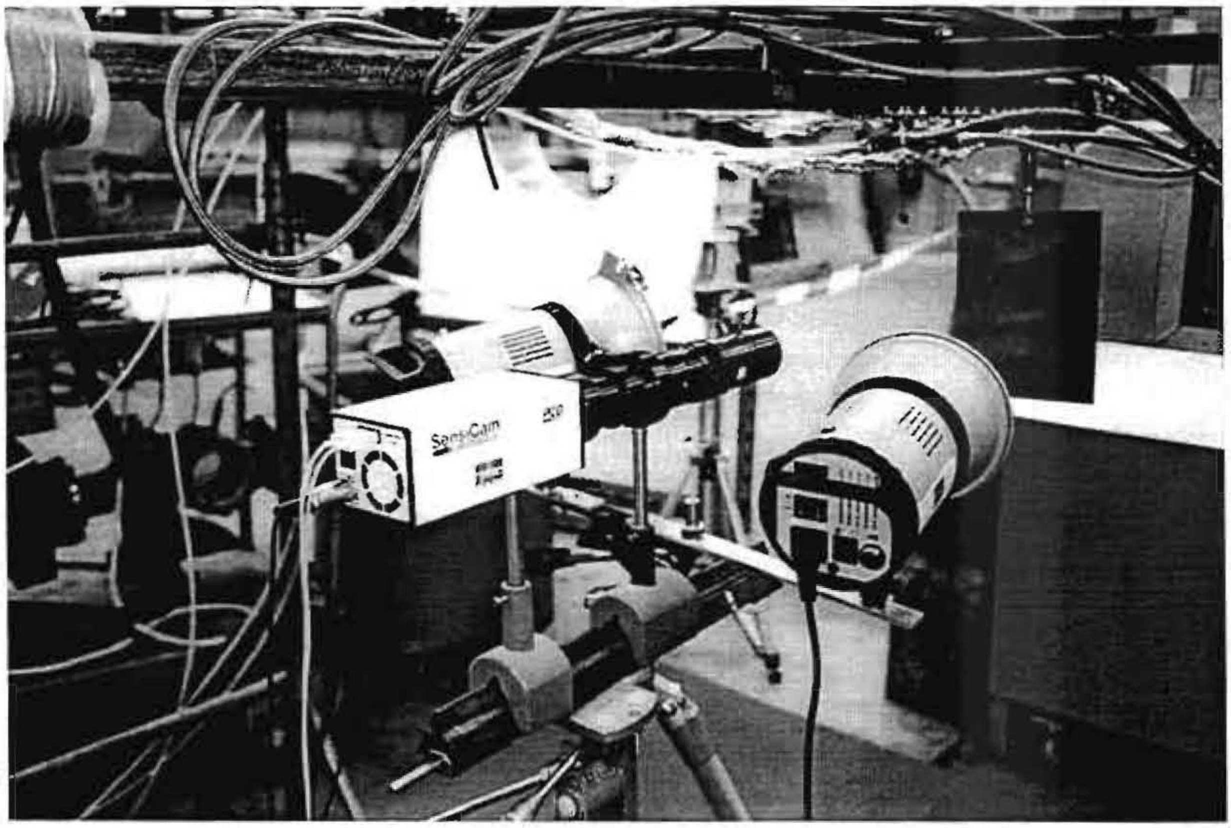

Figure 9 : High speed video capturing equipment

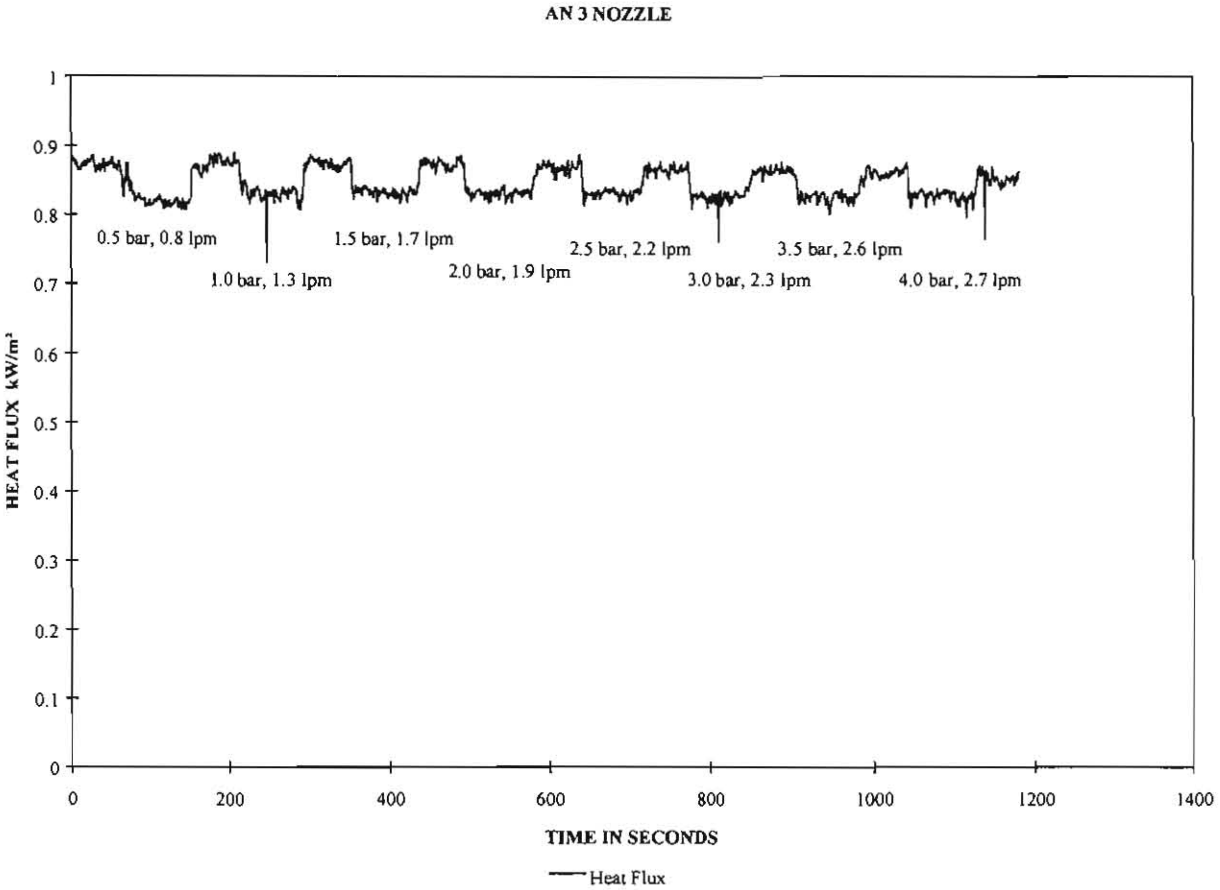

Figure 10 : Example of thermal attenuation results for a single AN3 nozzle

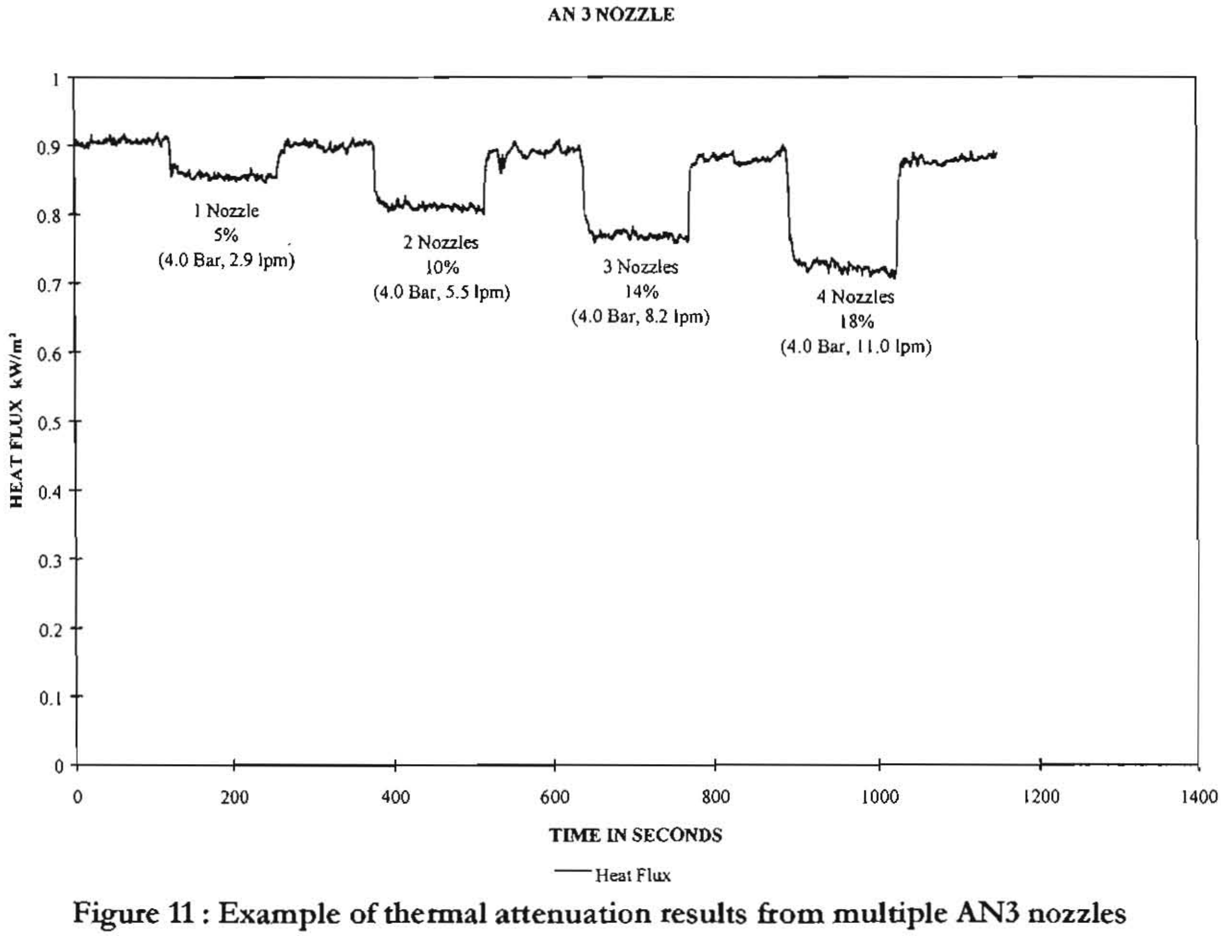

Figure 11 : Example of thermal attenuation results from multiple AN3 nozzles

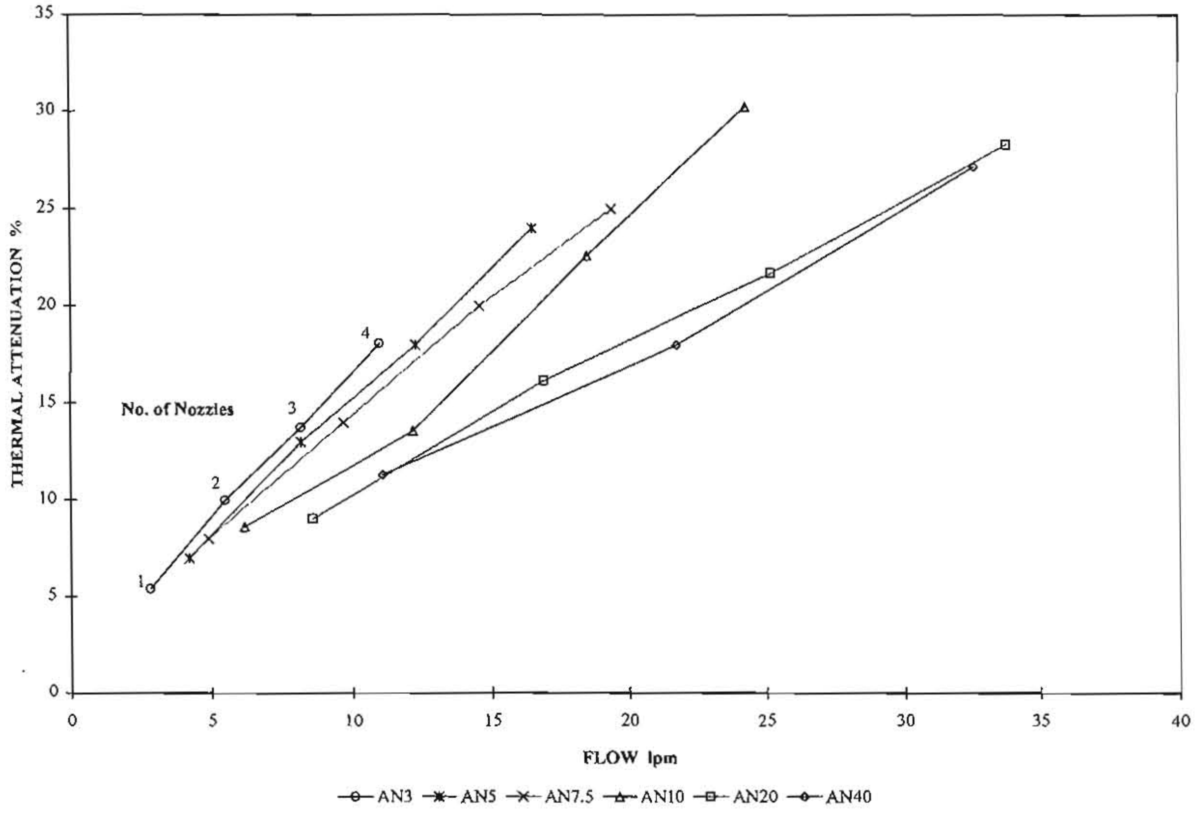

Figure 12 : Thermal attenuation results from all the multiple nozzle tests

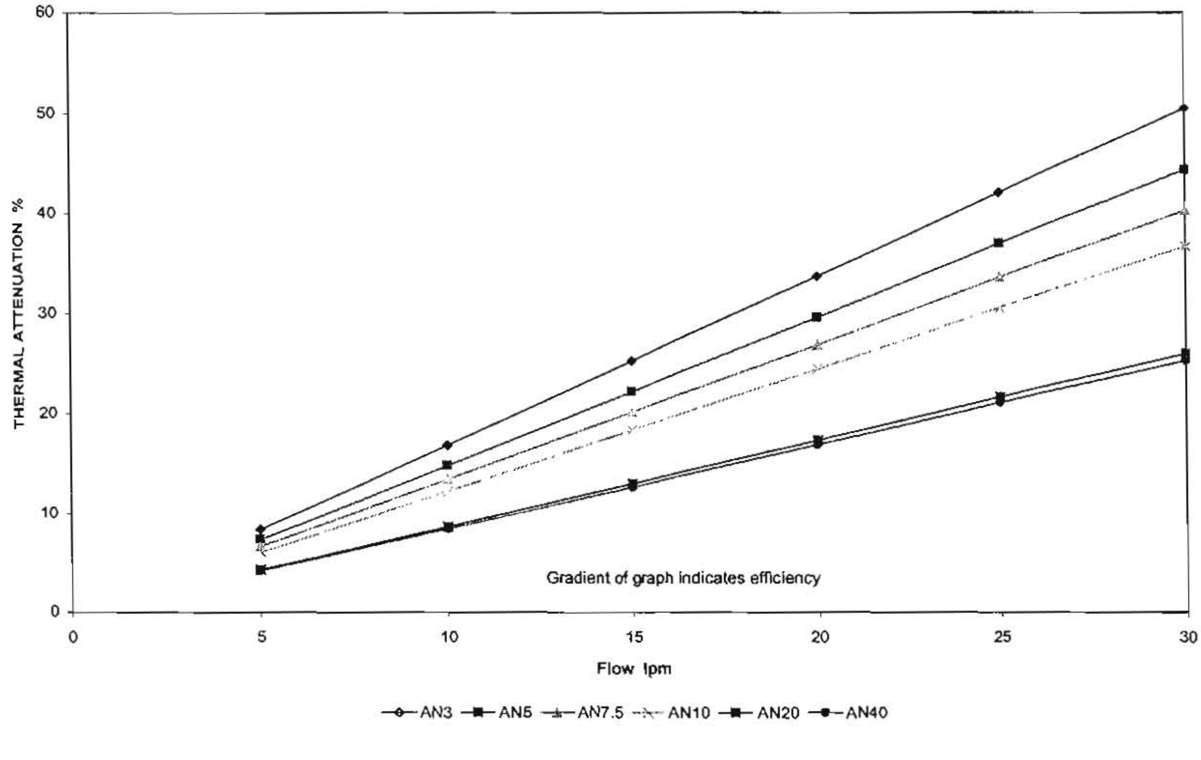

Figure 13 : Thermal attenuation as Figure 12 (after regression analysis)

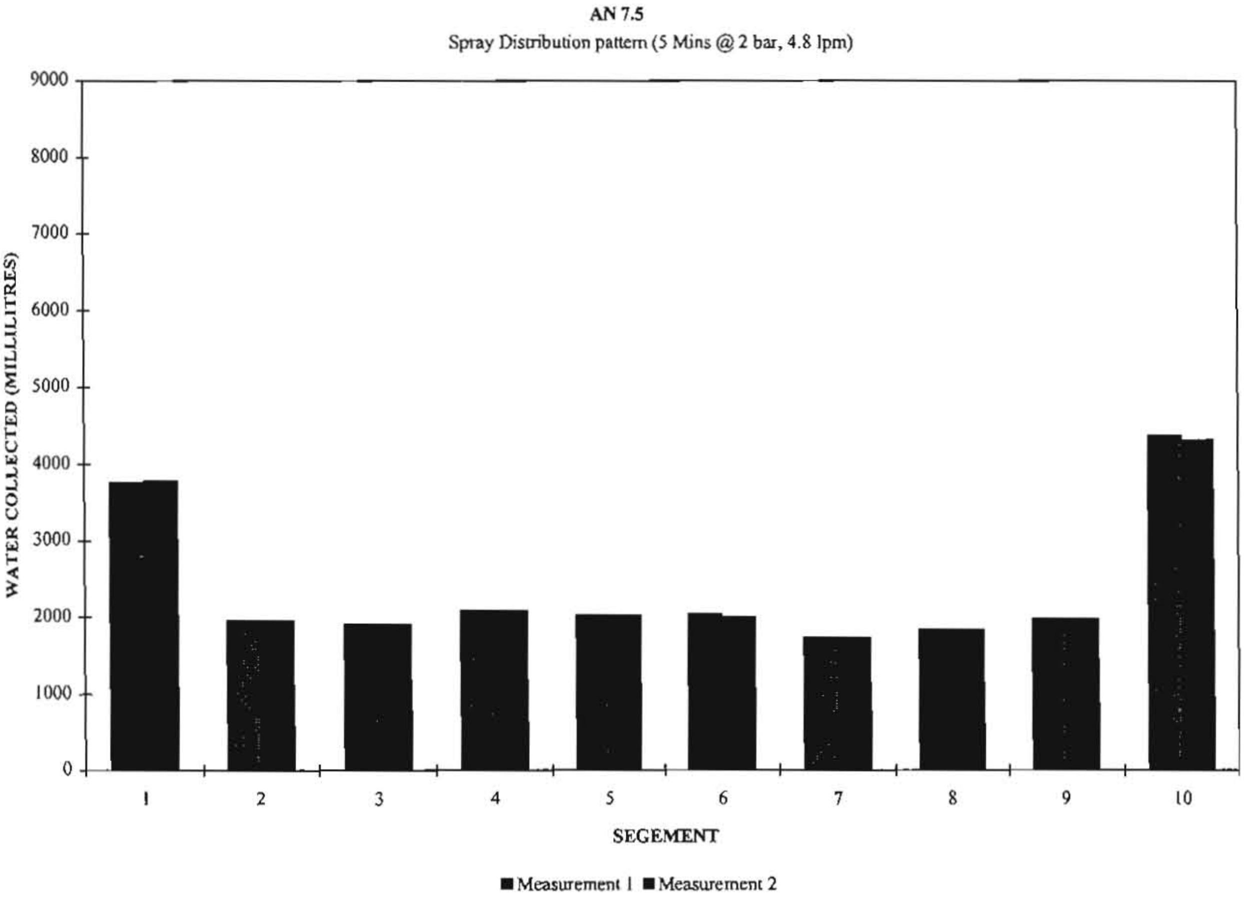

Figure 14 : Example of spray distribution results

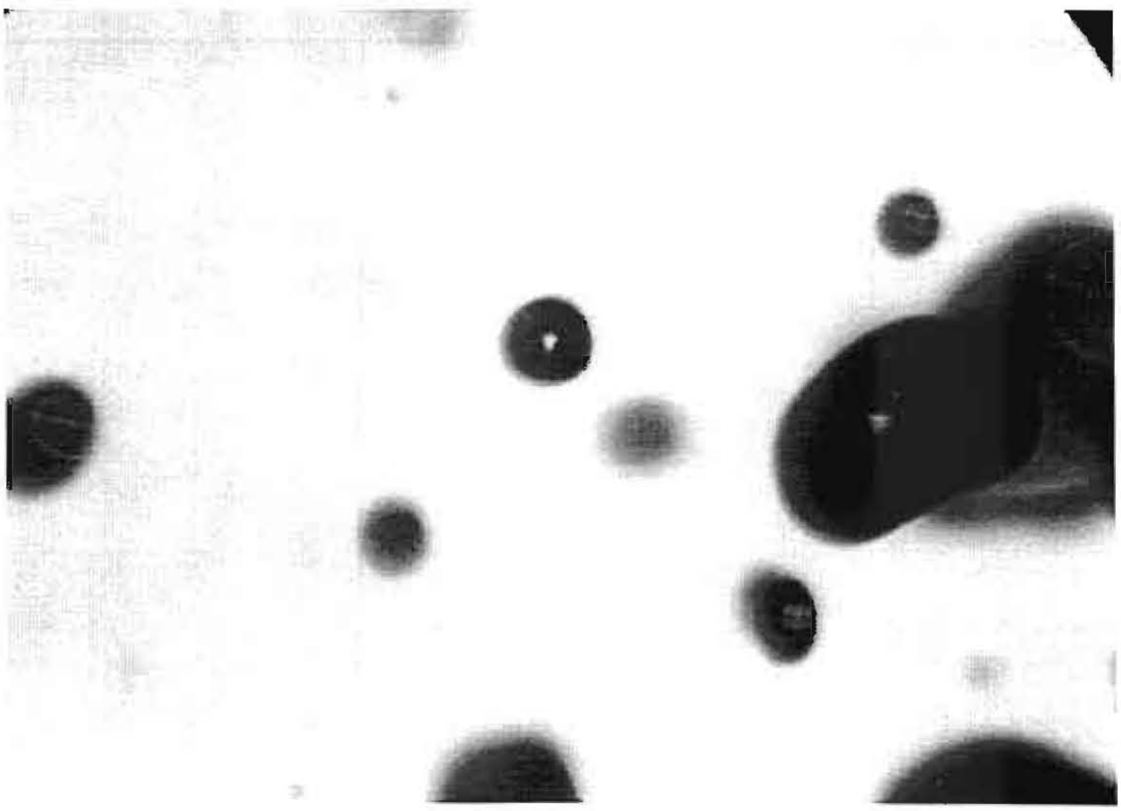

Figure 15 : Example of photograph of droplets

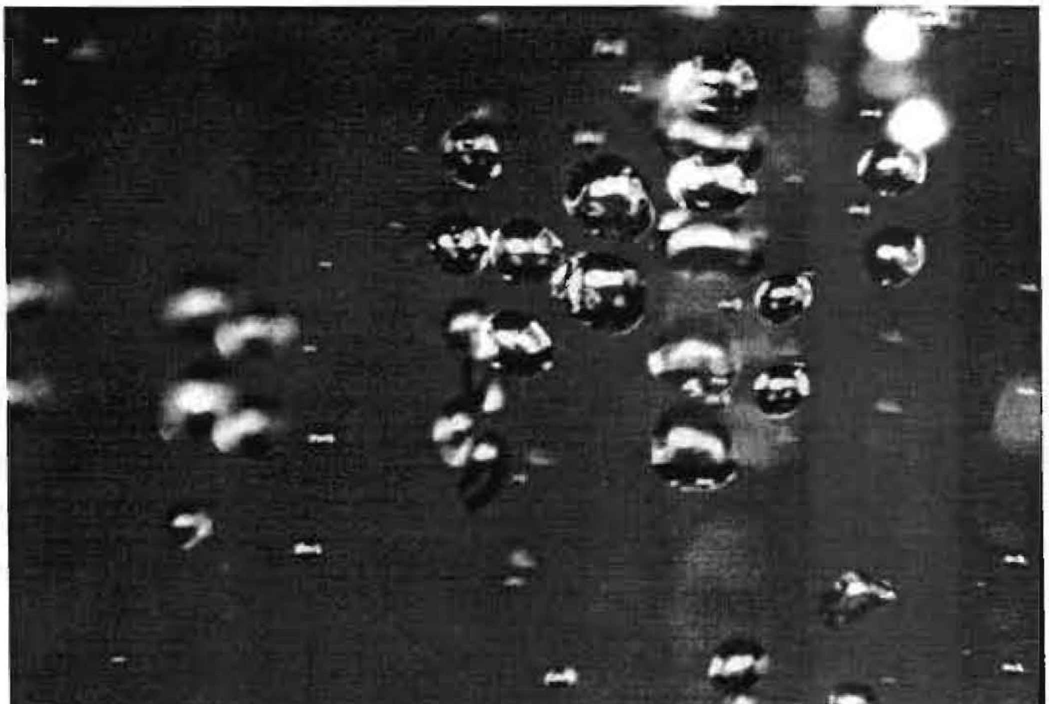

Figure 16 : Example of high speed video image of droplets

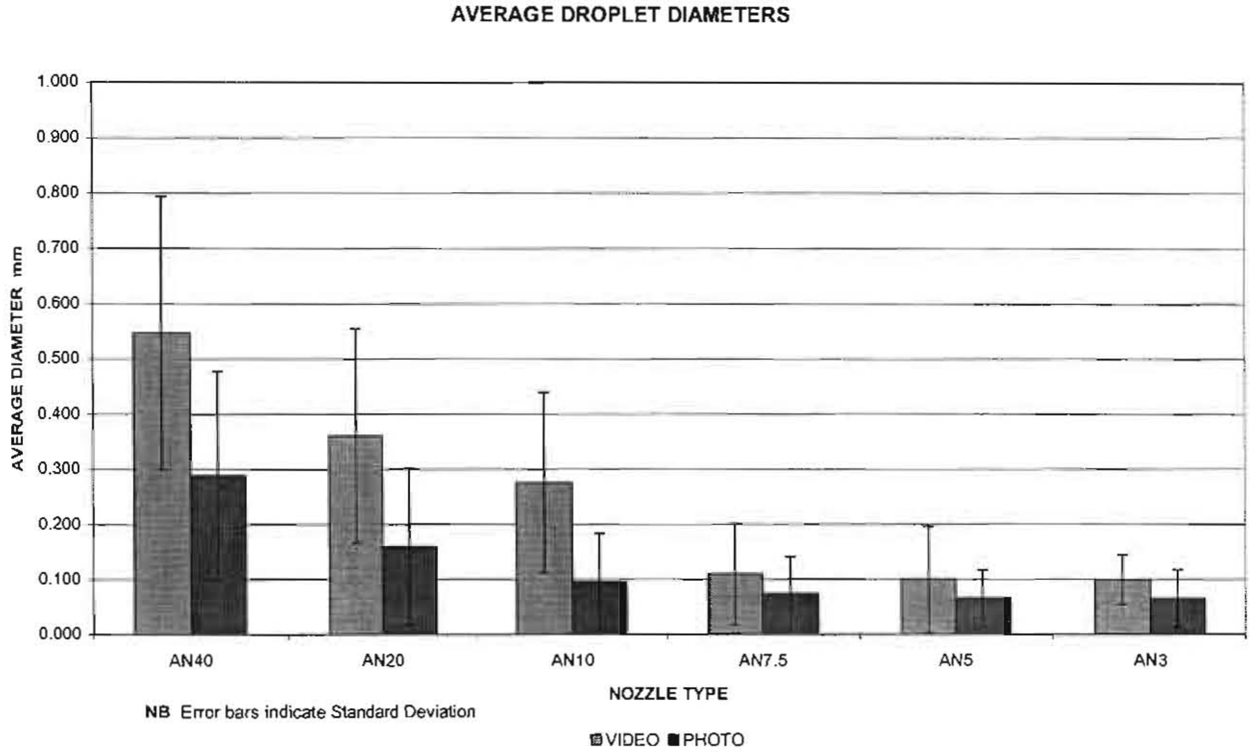

Figure 17: Average droplet diameters from photographic and video methods

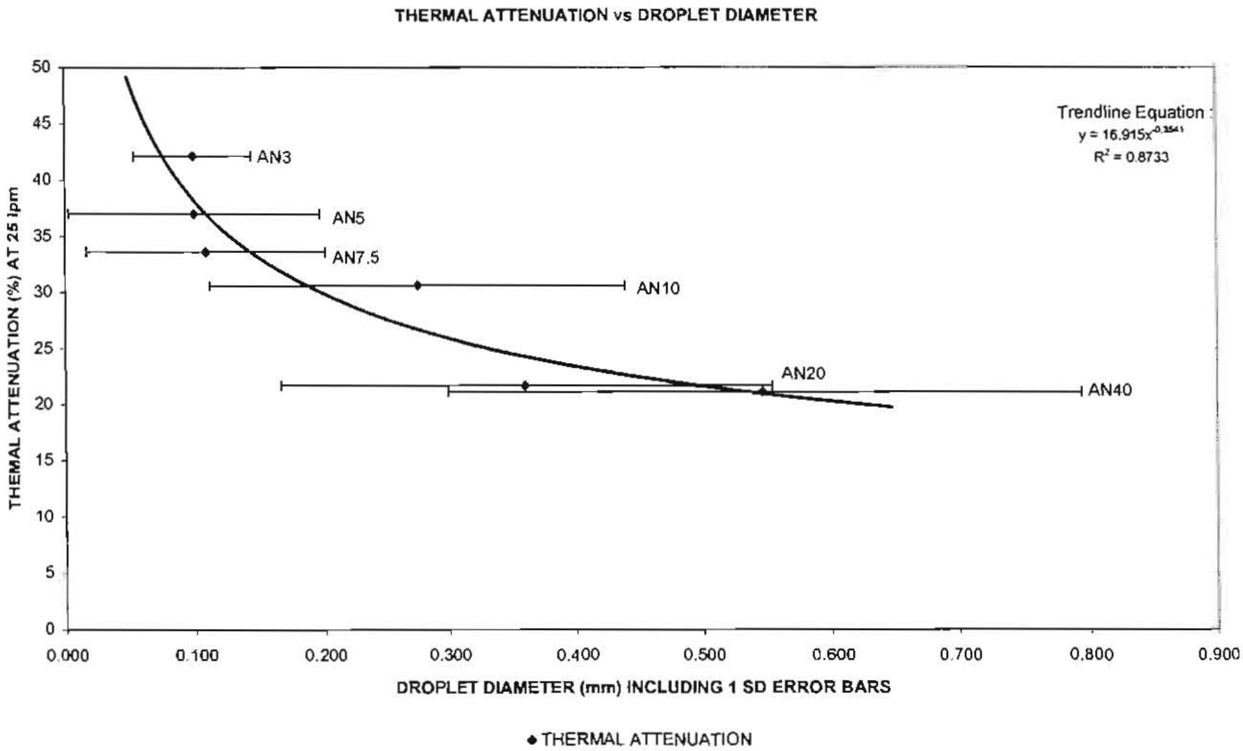

Figure 18 : Droplet diameter against thermal attenuation for all nozzle types

Appendix A : Method and results of data analysis including droplet size histograms from high speed video system

Data Analysis Method

1. For each frame a scaling factor was worked out between it and a 'Standard' frame size of 0 .0005 m^2

$$\text{Area Scaling Factor} = \frac{0.0005}{Frame\ Area\,(m^2)} = \frac{0.0005}{Width \times Height}$$

2. Droplet by droplet for all frames calculate the total spray flux in Litres per second thus:

$$1000 \times \left[\sum \frac{4}{3}\pi \left(\frac{D}{2}\right)^3 \times \frac{V Cos\,\theta}{y} \right]$$

where D = droplet diameter (m)
V = droplet speed (m/s)
θ = droplet angle (degrees)
y = frame height (m)

3. Calculate the average flux per frame by dividing total flux by the number of frames

4. Find the arc length of one collecting box at the sample position using trigonometry

Length of arc = 0.0047 m

5. Total calculated flux = $Average\ Flux \times \frac{Arc\ Length}{Frame\ Width}\ (lps)$

6. Work out a depth scaling factor

$$\text{Depth Scaling Factor} = \frac{Actual\ Measured\ Flow}{Total\ Calculated\ Flux}$$

The actual measured flow value is obtained from the spray distribution measurements. This is the average of 4 measurements from the central segments (5 & 6) of the spray catching device.

7. Droplet size bands were then chosen to cover the range of the smallest to the largest drop diameters. These were chosen at 0.05 mm intervals from 0 to 1.5 mm.

8. A grand distribution of droplets in the total spray was then calculated

$$\text{Grand Distribution of drops} = \frac{\left(\dfrac{Number\ of\ drops\ in\ each\ band}{Area\ Scaling\ Factor^2}\right)}{Number\ of\ frames} \times Depth\ Scaling\ Factor$$

9. For each band calculate the total area of those droplets in that band and sum all of the band areas together to get a figure for the total droplet area.

$$\text{Total Droplet Area} = \sum \frac{\pi D^2}{4} \times \textit{Number of drops in each band}$$

10. Calculate the percentage of the 'Standard' area that is covered by the calculated total droplet area

$$\text{\% of Standard Area covered} = \frac{\textit{Total Droplet Area}}{0.0005} \times 100$$

Results

Test	Nozzle	Flow Lps	Attenuation %	Speed m/s	Arithmetic mean diameter Microns	Std dev	% of standard area	Field of view mm²	No. of drops measured
1 & 2	AN40	0.017503	11	7.65	498	168	158.4316	498.3	106
3 & 4	AN40	0.017503	11	7.56	617	258	0.514013	99.0	61
21	AN40	0.017503	11	8.19	592	428	0.061922	57.9	21
5 & 6	AN20	0.013167	9	10.98	370	207	0.471077	98.5	158
7 & 8	AN20	0.013167	9	10.01	290	133	0.037128	54.8	41
20	AN20	0.013167	9	10.91	382	183	0.127104	59.2	60
9 & 10	AN10	0.009059	9	14.74	319	162	0.021908	58.3	32
19	AN10	0.009059	9	7.45	136	53	0.003674	12.5	10
12	AN7.5	0.006762	8	5.04	86	24	0.005353	10.7	9
13	AN7.5	0.006762	8	5.47	99	88	0.000173	6.1	29
18	AN7.5	0.006762	8	6.70	139	112	0.000676	11.9	17
14	AN5	0.006059	7	4.29	68	27	0.000797	6.1	23
17	AN5	0.006059	7	6.18	135	129	0.000412	12.4	21
15	AN3	0.003983	5	5.28	88	48	0.000146	5.8	13
16	AN3	0.003983	5	5.50	104	42	0.001881	12.4	30

Table A1 : Detailed droplet results from high speed video method

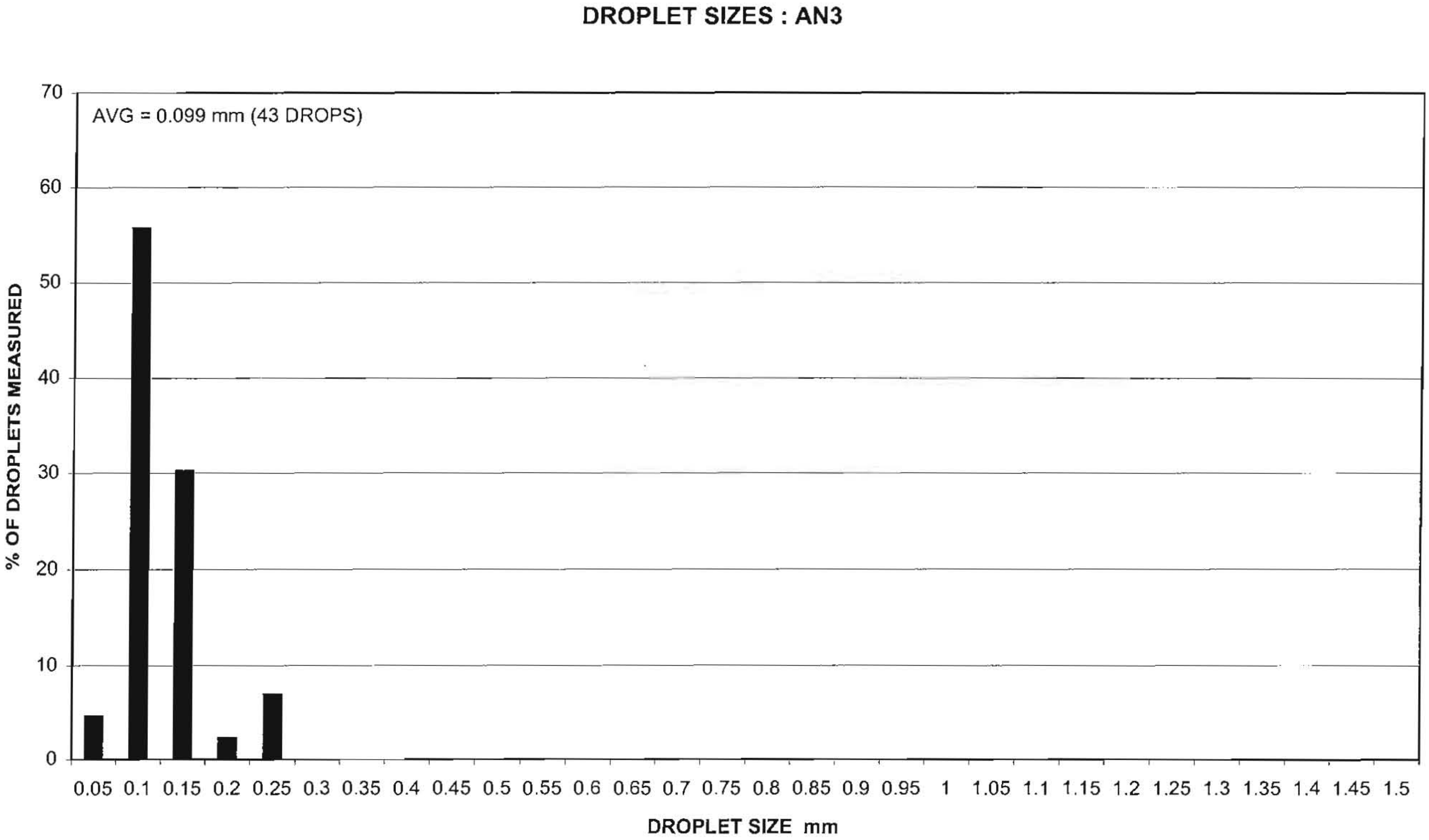

Figure A1 : Histogram of droplets produced by AN3 nozzle

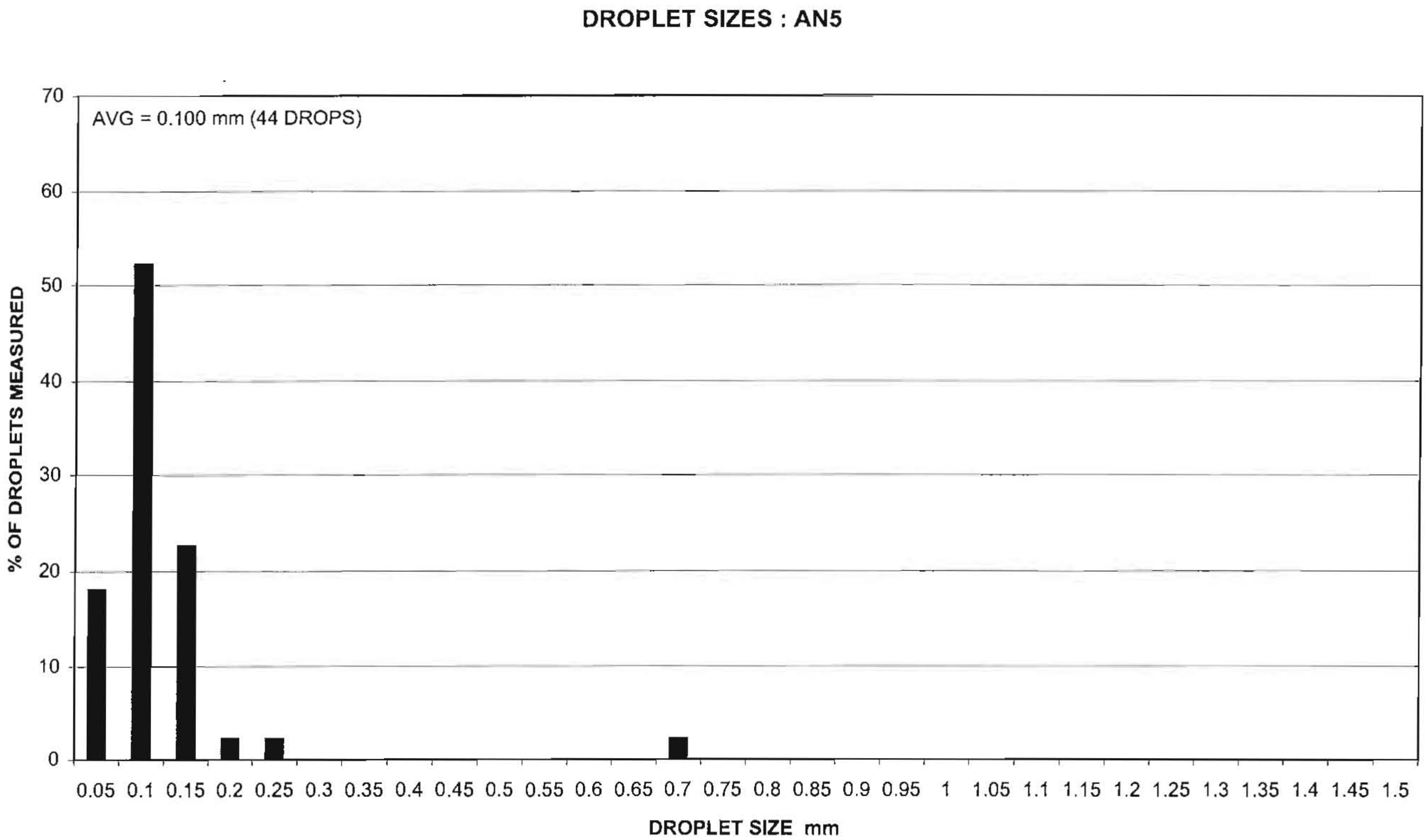

Figure A2 : Histogram of droplets produced by AN5 nozzle

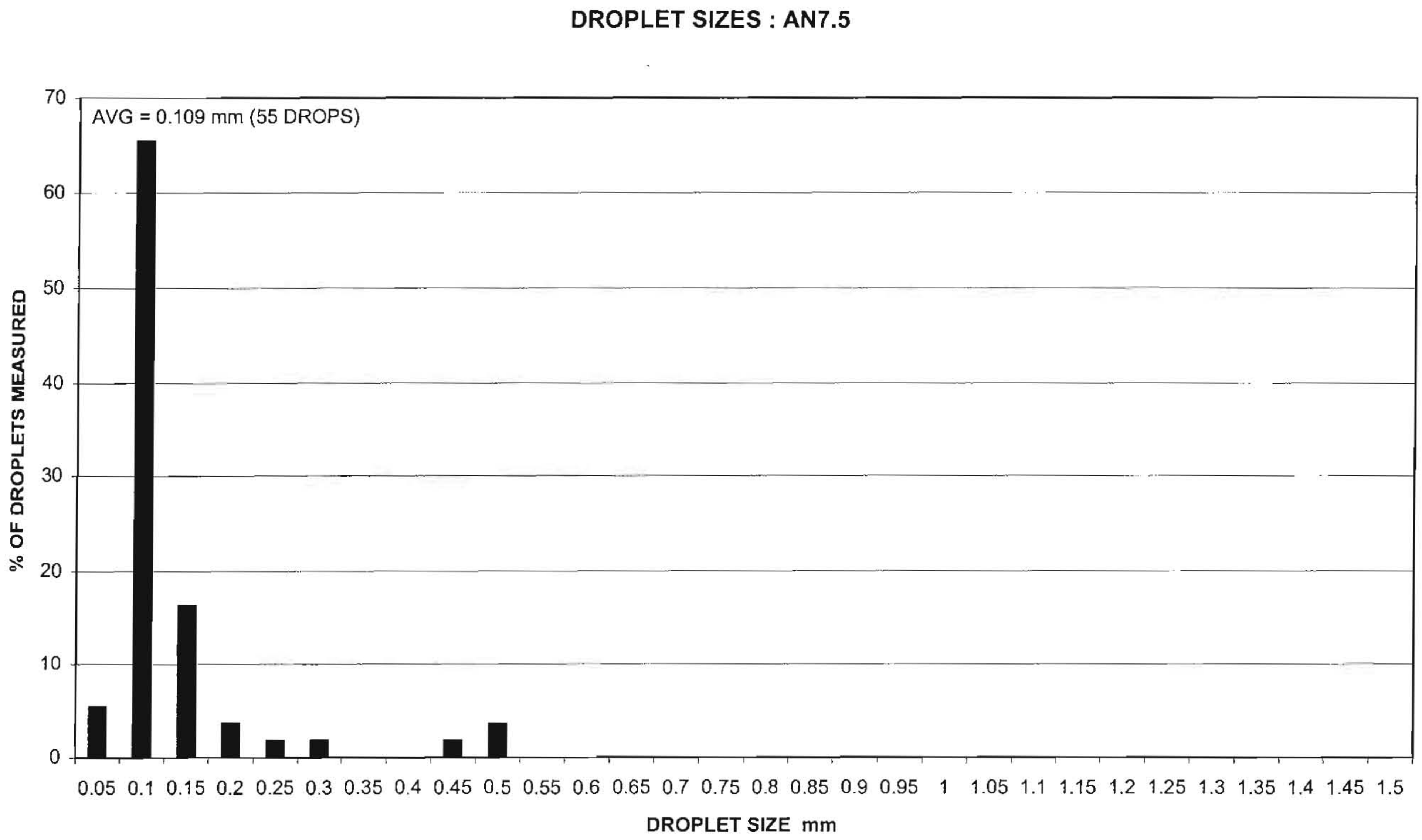

Figure A3 : Histogram of droplets produced by AN7.5 nozzle

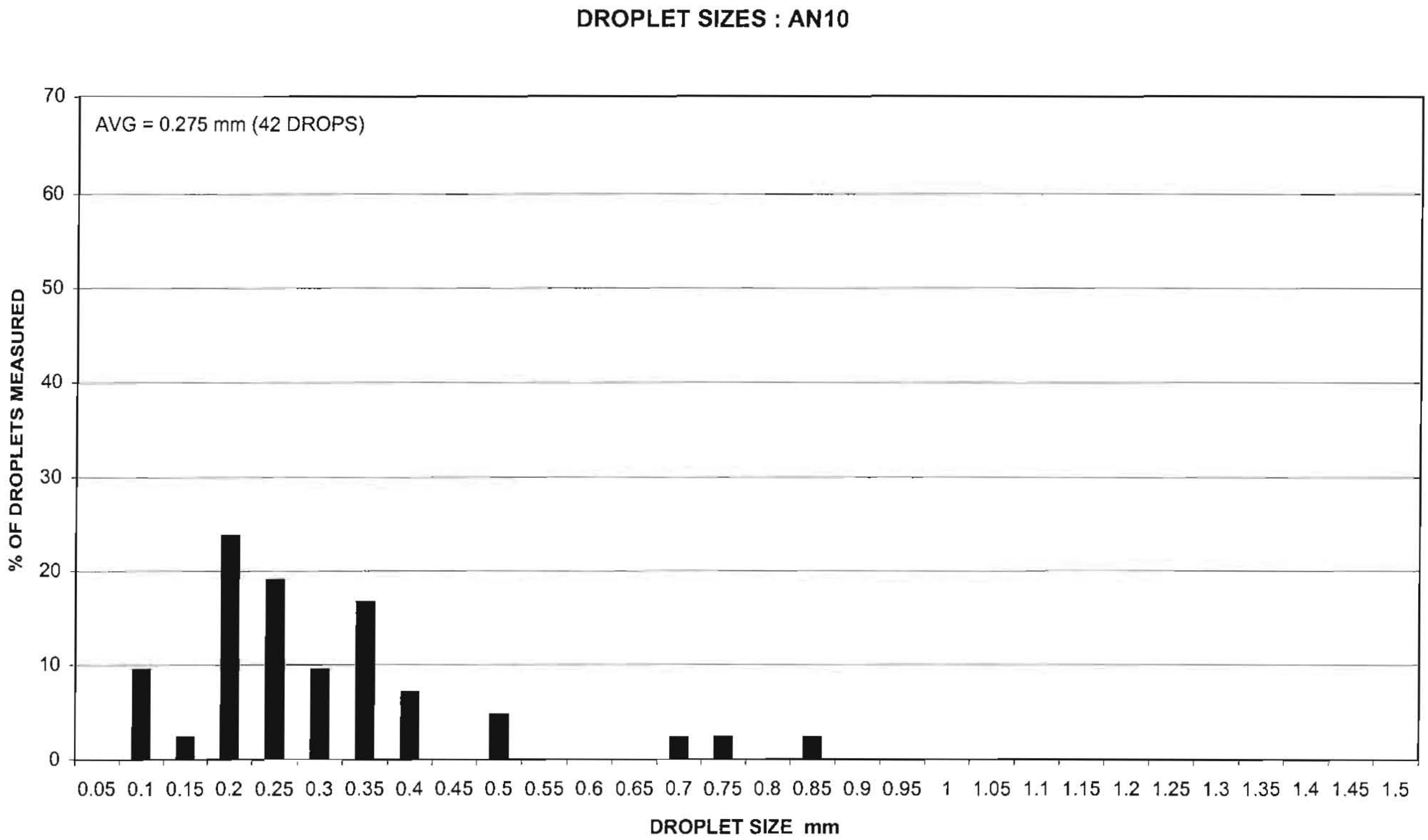

Figure A4 : Histogram of droplets produced by AN10 nozzle

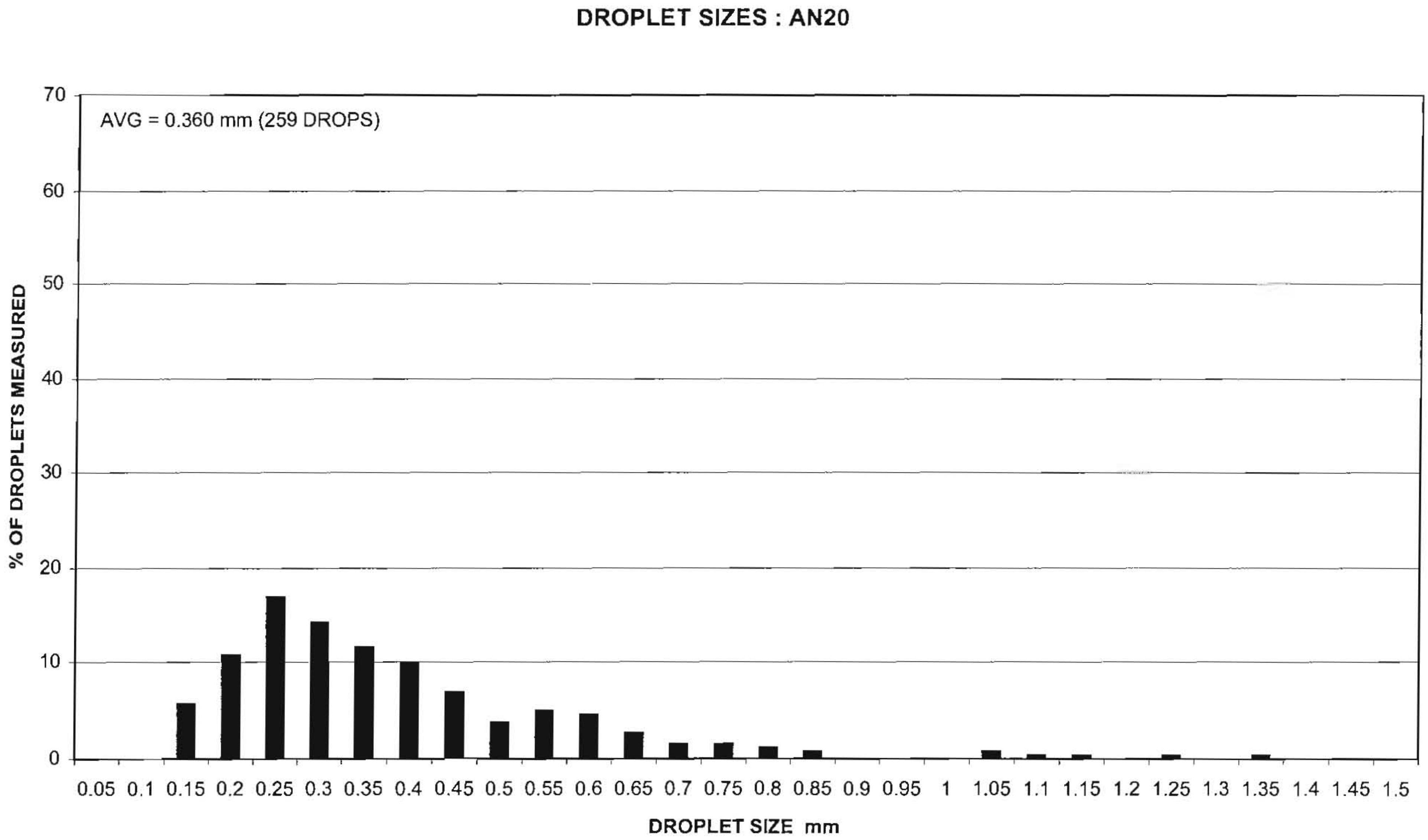

Figure A5 : Histogram of droplets produced by AN20 nozzle

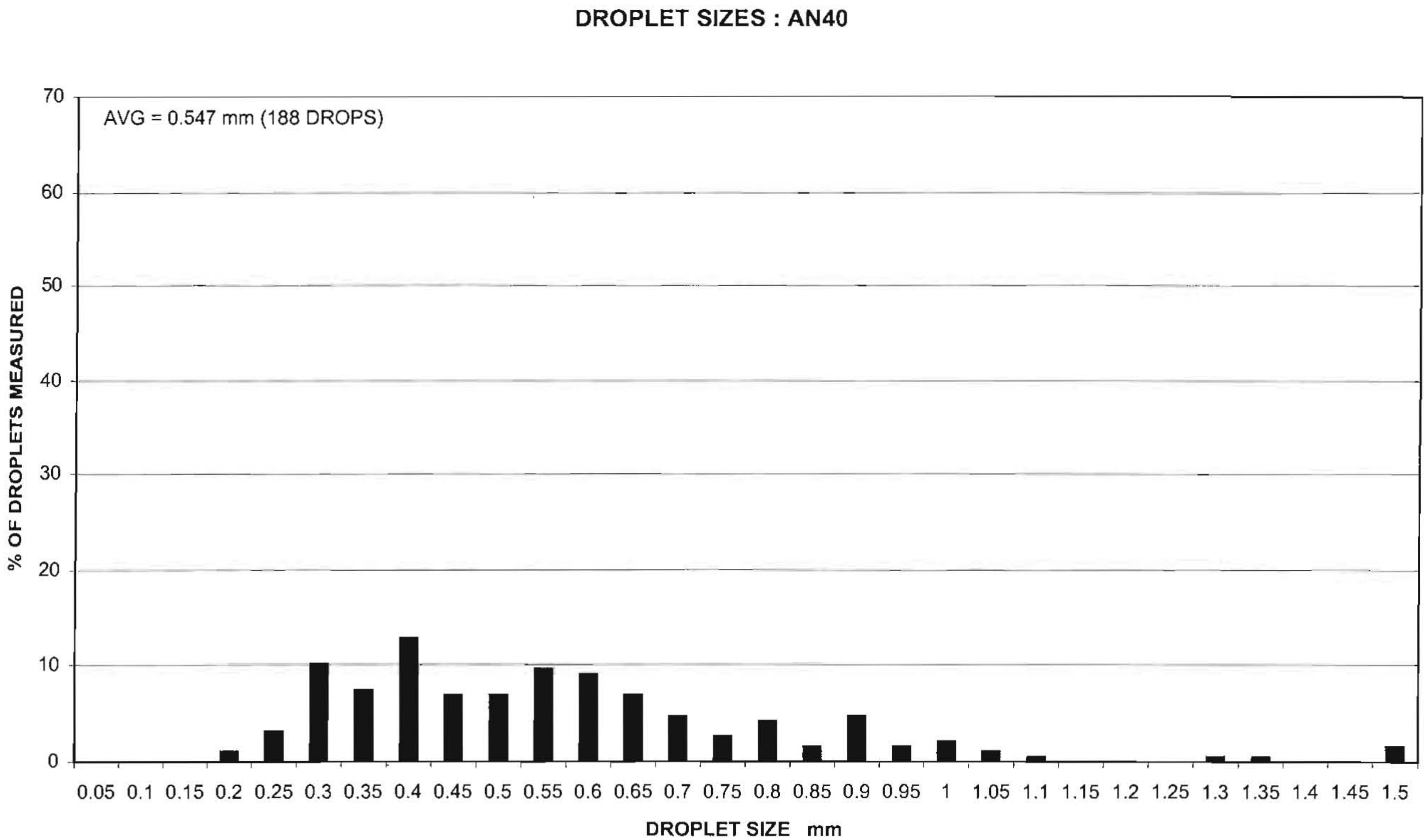

Figure A6 : Histogram of droplets produced by AN40 nozzle

Appendix B : Histograms of droplet sizes from the photographic method

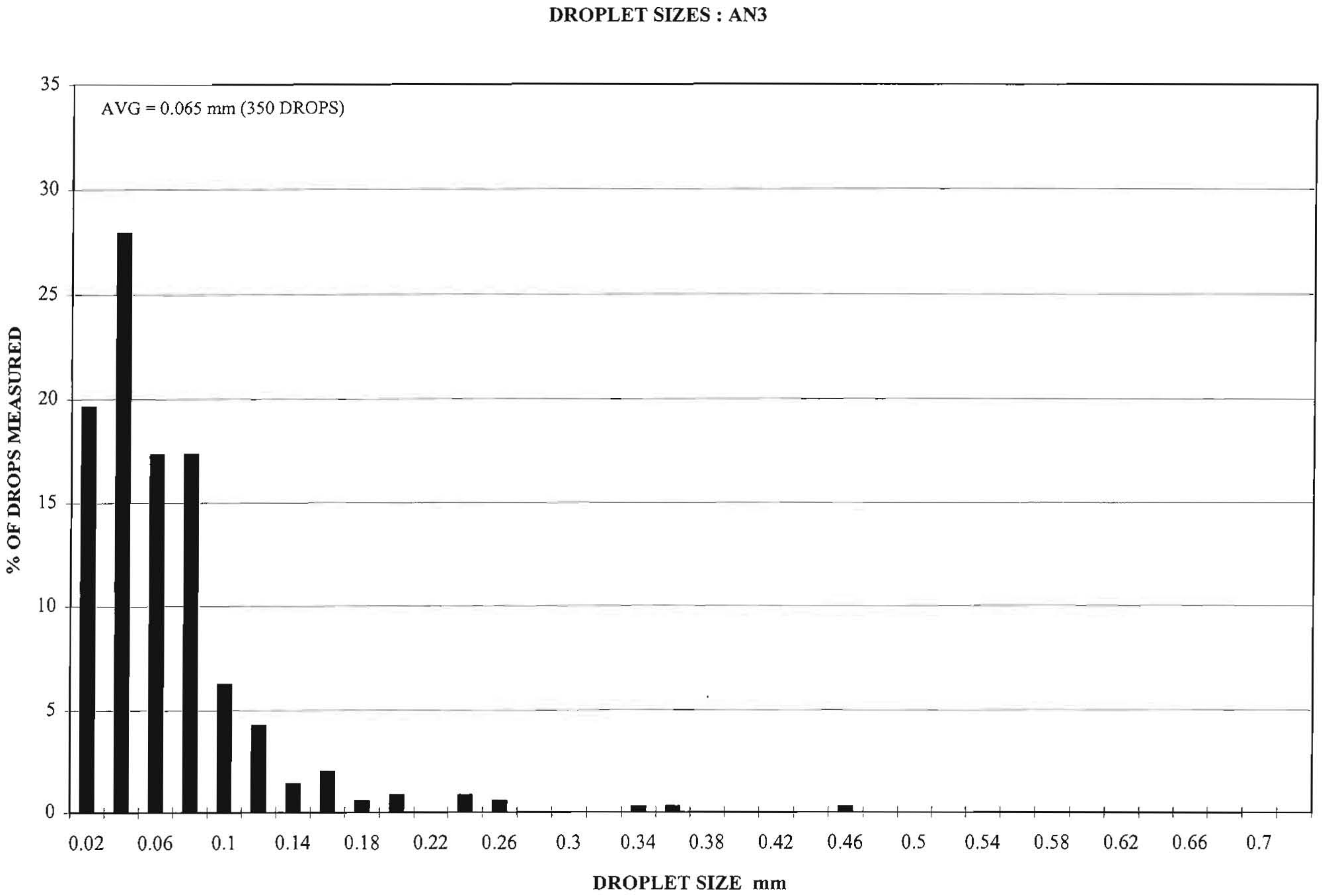

Figure B1 : Histogram of droplets produced by AN3 nozzle

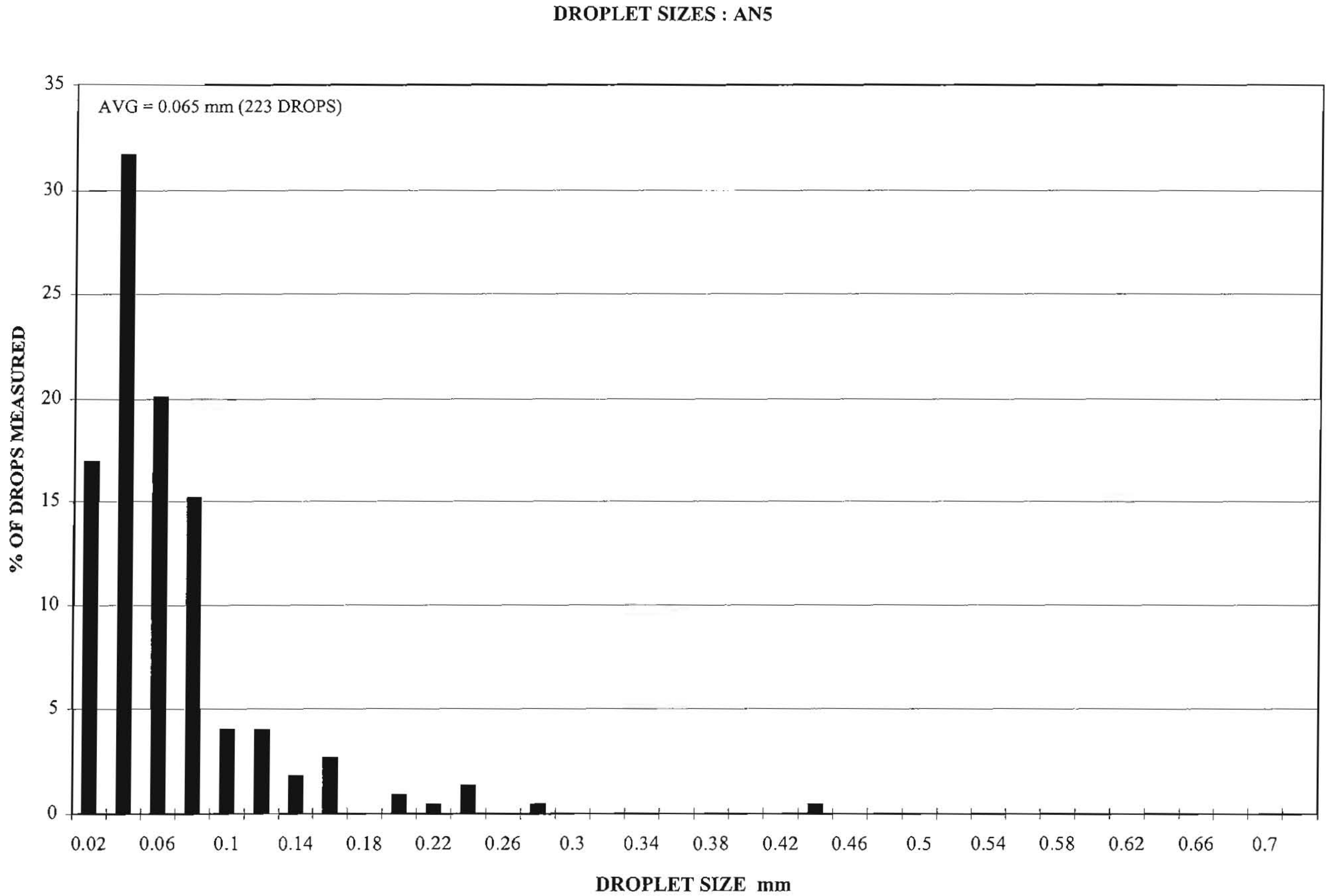

Figure B2 : Histogram of droplets produced by AN5 nozzle

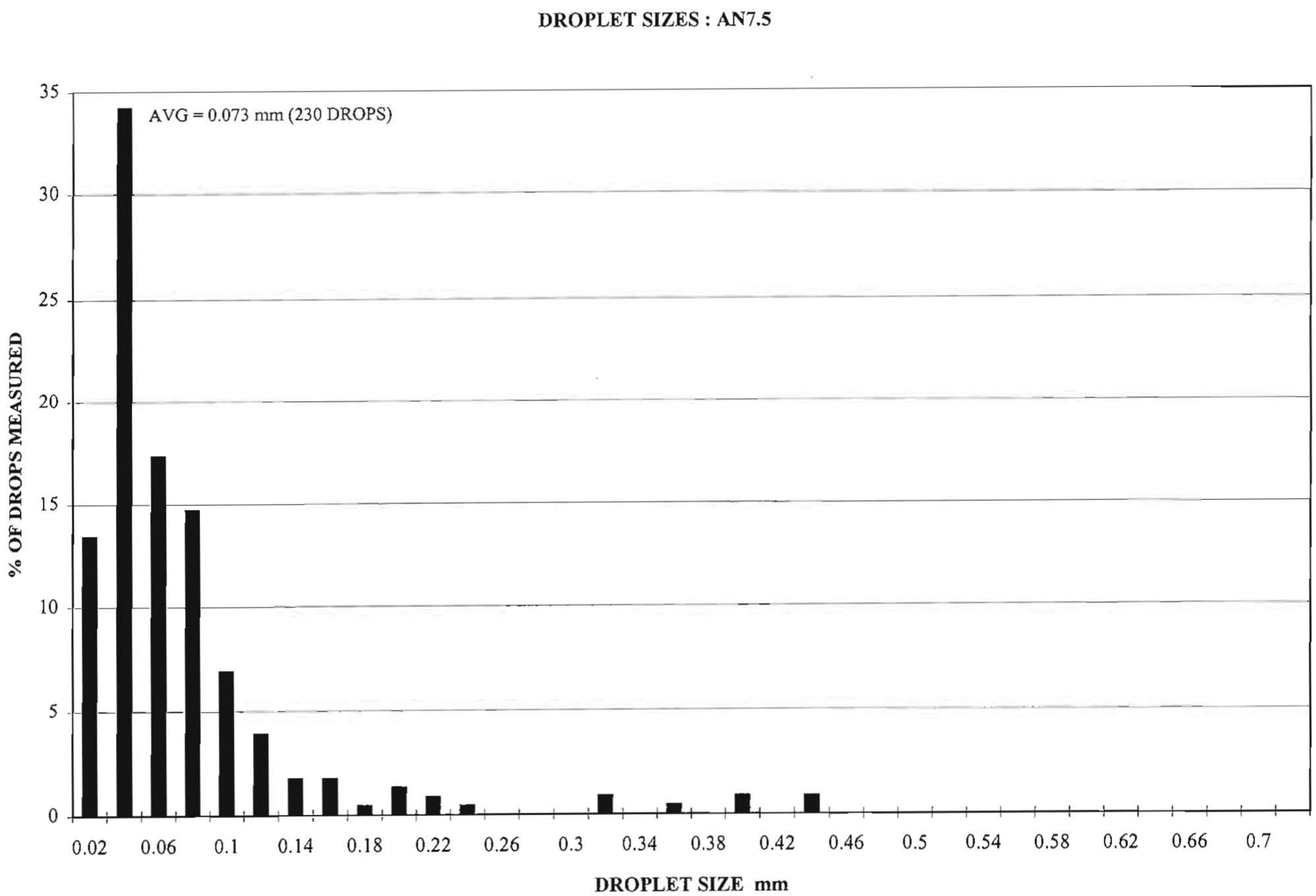

Figure B3 : Histogram of droplets produced by AN7.5 nozzle

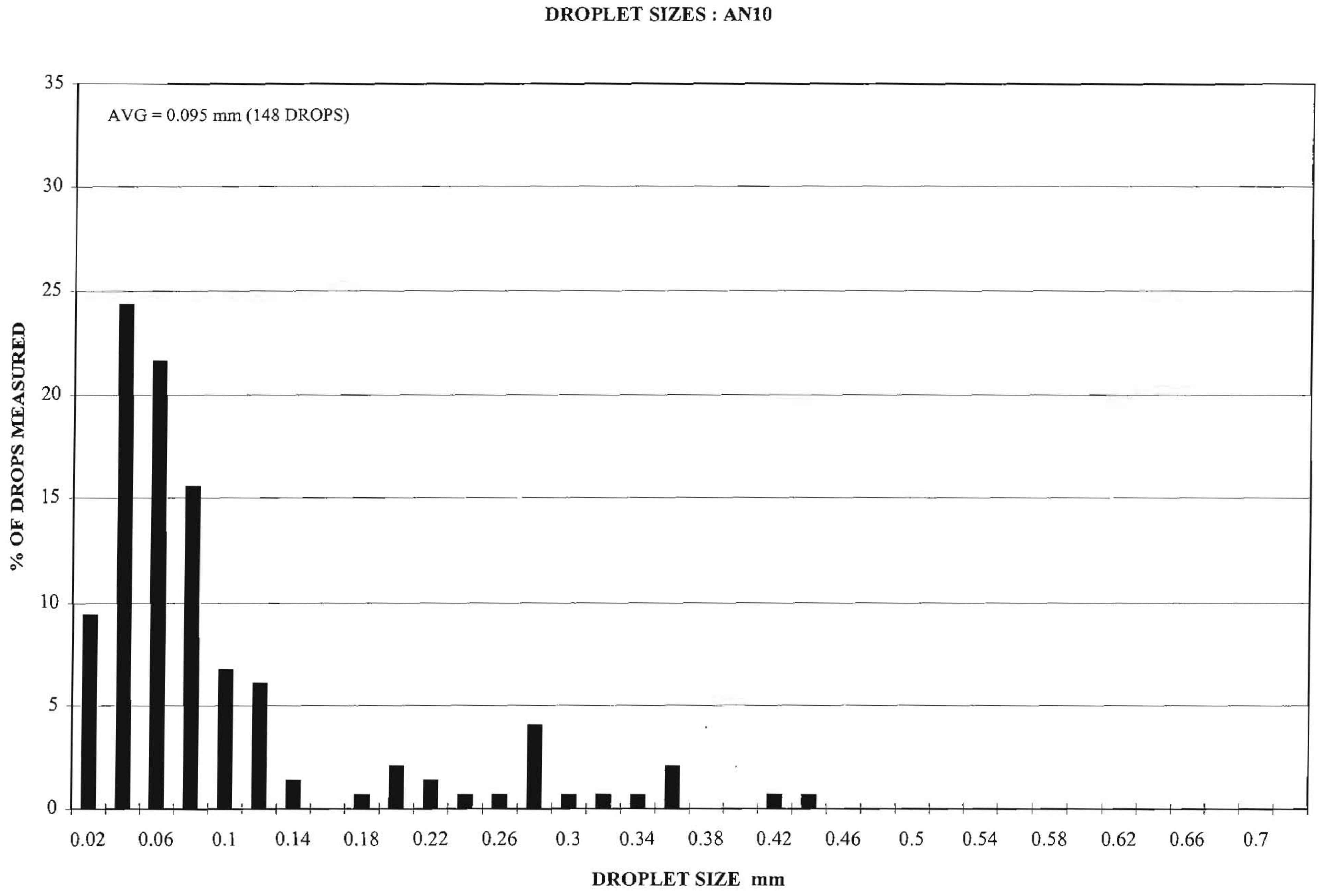

Figure B4 : Histogram of droplets produced by AN10 nozzle

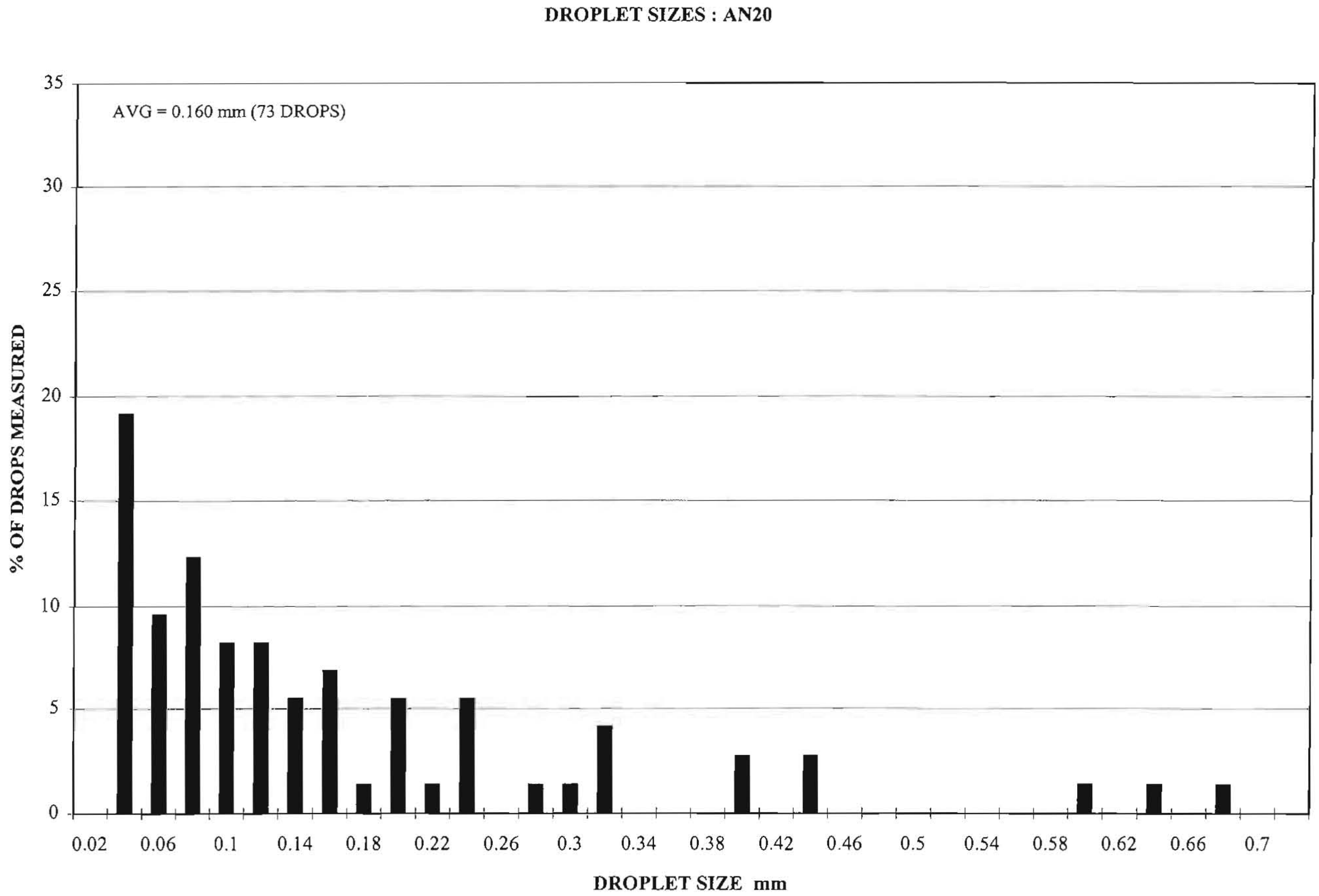

Figure B5 : Histogram of droplets produced by AN20 nozzle

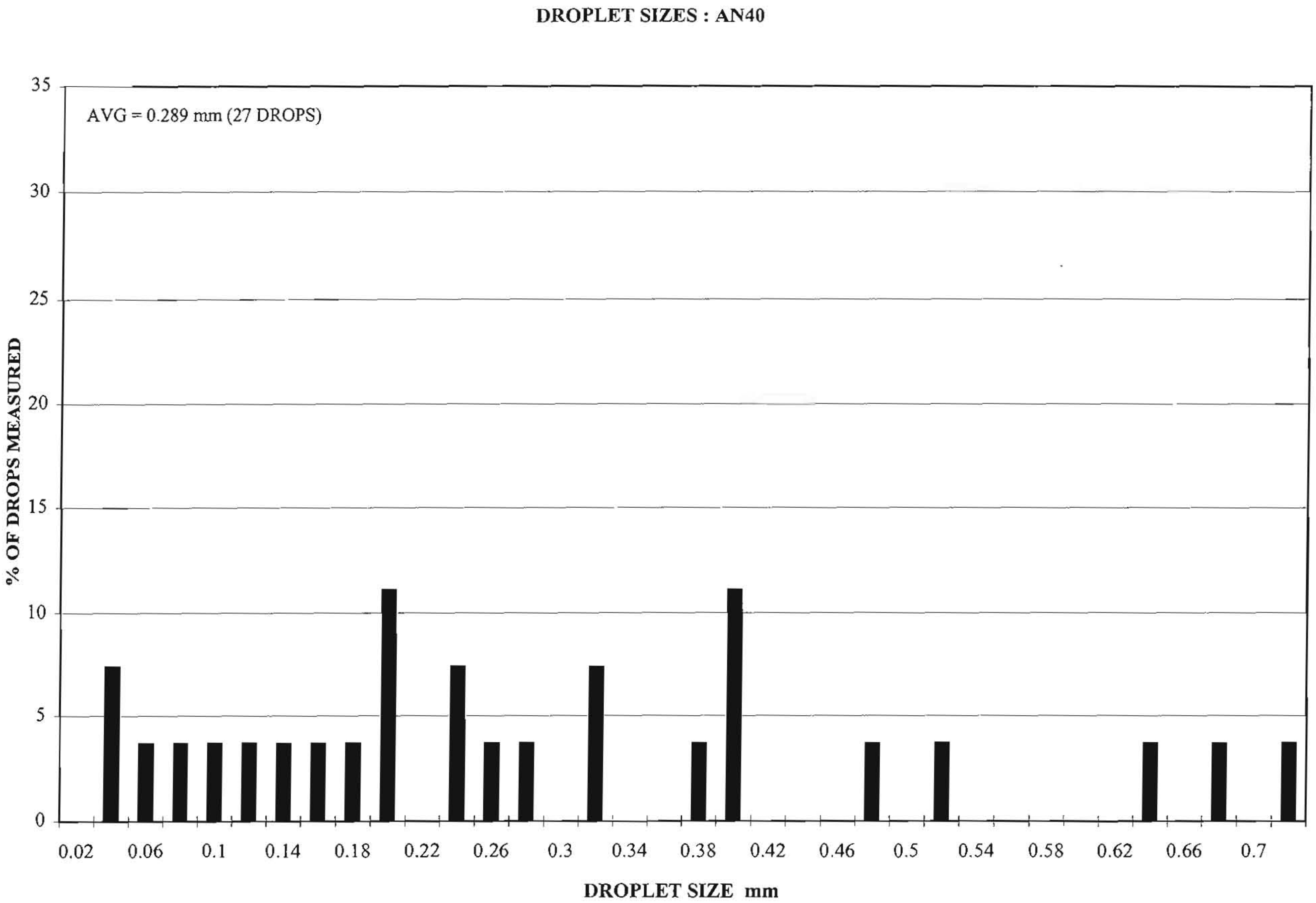

Figure B6 : Histogram of droplets produced by AN40 nozzle