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PROTOCOL FOR TESTING PERFORMANCE OF FOG NOZZLES FOR GAS TURBINE INLET FOGGING APPLICATIONS

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1.0 ABSTRACT

There is no existing standard of droplet size measurement for gas turbine inlet air fogging applications. ASTM has provided overall guidelines but does not specify the details of test procedure to be used in the fogging industry. The result is that the user is confronted by data that is impossible to reconcile. Further there are several aspects of testing that bear relevance to the application of fog to gas turbine engines. To overcome this problem, a new measurement standard has been developed by Mee Industries Inc, and is proposed here. The measurement standard incorporates the following:

Defines the instrumentation to be used.
Defines locations where measurements are to be made.
Defines the airflow velocities under which the measurements should be made.
Defines the averaging approach and representative diameters to be used.
Defines the final report format to be used.

2.0 INTRODUCTION

This test protocol gives procedures for droplet size measurement relative to fog nozzles for inlet fogging of gas turbine engines. It specifies the test parameters and methods for determining the performance of nozzle atomization. For the purpose of this protocol, the device includes nozzles (Impaction-pin or Swirl-jet nozzles), tubing from SS, high-pressure pump, and size measurement systems.

The experiment is to be done in wind tunnel, which presents conditions similar to real word gas turbine inlet duct conditions.

The purpose of this protocol is to ensure consistent, relevant testing and presentation of atomization performance data. Any change in the device specification would necessitate re-testing to demonstrate acceptance under this protocol.

A laboratory possessing the appropriate equipment, staff, experience and procedure for droplets sizing and analysis shall carry out tests.
The laboratory shall be <u>independent</u> of the manufacturer and approved for the testing or calibration relevant to this protocol.

Testing shall be done in presence of nozzles manufacturer representatives when requested who would observe the setup and tests on a non-interference basis.

This test is intended for use to study the fog nozzles performance relating to droplet sizing using optical techniques. Two type of instrument may be used and will be described in this test:
video camera (imaging technique), and Light Scattering use optical (non imaging techniques) phenomena.

This document represents a standard of good practice. It will help users to avoid pitfalls that may lead to questionable or erroneous data, and also minimize differences between operators and different systems, and improve data comparison between different measurement techniques.

3.0 ASTM REFERENCES

E 799-92: Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis.
E 1088: Definitions of Terms Relating to Atomizing Devices.
E 1260-88: Standard Test Method for Determining Liquid Drop Size Characteristics in a Spray Using Optical Non-Imaging Light-Scattering Instruments.
E 1296-92: Standard Terminology Relating to Liquid Particle Statistics.
E 456: Terminology definitions; Quality and Statistics.
E 799-92 (1998): Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis.
E 1458-92 (2001): Standard Test Method for Calibration Verification of Laser Diffraction Particle Sizing Instruments Using Photomask Reticules.
E 177-90a(1996): Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods.
STP 848: Liquid Particle Size Measurement Techniques.
STP 1083: Liquid Particle Size Measurement Techniques Vol. 2.

4.0 TERMINOLOGY

Ambient: of/or relating to immediate surroundings.
Atomization: Mechanism that leads to the production of droplets which vary in diameter depending on the process.
Concentration Volume (CV): which is the concentration volume given in parts per million. CV also gives an indication of liquid water content (1 CV is equal to one cubic centimeter of liquid water per cubic meter of air.
Demineralized water: Removal of mineral constituents from water.
Droplet size: diameter of a droplet by assuming spherical shape, expressed in micrometers (m).
Erosion: A physical or mechanical wearing process rather than a chemical solution process in which a stream of liquid or air wears material away.
Filter: Separate particles from water going through semi-permeable medium.
Filtration: Process of what particles are separated form water when passing through semi-permeable material.
Flow Rate: Quantity of liquid flowing through a nozzle in gallons per minute (gpm), liters per minute (l/min).
Fog Droplets: Very fine water droplets, produced artificially using appropriate nozzle or device, with size varying between 2 and 70 microns.
Impaction-pin nozzle: water is forced through a smooth orifice and the high-velocity jet is directed at an impaction-pin located above the orifice. The impaction of the water jet on the pin results is a thin sheet of water in a conical shape. As the conical sheet extends away from the nozzle orifice the surface area of the sheet expands so that the water-sheet becomes increasingly thinner which is break down into "fingers" of water and aerodynamic instabilities cause the fingers to break into ligaments and then into droplets.
Micrometers, or microns (m): Linear measure equal to one millionth of a meter
Operating pressure: the range of pressure, usually expressed in psi over which water is forced through nozzle orifice.
Pressure drop: Pressure difference under flow conditions, measured before and after the nozzles manifold and expressed in inch of water gauge.
Psi: Unit of pressure (pounds per square inch).

Spatial technique: In use to measure droplet size done in a given volume during a lapse interval of time where the content of this volume did not change during this time.
Swirl-jet nozzle: the fluid is forced to enter tangentially into the swirl chamber taking a helical path before discharging through a cylindrical hole concentric to the swirl chamber. This leads to the formation of an air core with a larger diameter in the swirl chamber, as compared to the one in the orifice. The swirling jet results in the formation of an axisymmetrical, thin conical water sheet. The conical sheet breaks down in to ligaments and then small droplets.
Temporal technique: In use to measure droplet size of flux of droplets traversing a giving area during a given period of time.
Transmission: which is the percent light transmission through the spray. If this value is below a certain limit, the spray density may be too high and multiple-scattering errors may result.

5.0 DEFINITION OF MEAN DIAMETERS

Arithmetic Mean Diameter (AMD) D_{10}: The simple average diameter of all the droplets in a spray. D10 is equal to the sum of the diameter of all the droplets divided by the quantity of droplets.
Surface Area Mean Diameter (SAMD) D_{20}: The droplet diameter is measured directly using an imaging system. The SAMD diameter is then calculated on the basis of the droplets surface area. By taking the square of the diameter of each droplet, it is possible to calculate its surface area:

$$A_d \qquad D_d^2 \tag{1}$$

An average surface area is then calculated using the sum of the surface areas of all the droplets divided by the number of droplets. The square root of the average surface area is then divided by   to get the SAMD. The SAMD value characterizes the spray by giving the diameter of a hypothetical droplet that has a surface area equal to the average surface area of all the measured droplets.
Volume Mean Diameter (VMD) D_{30}: This characteristic diameter is calculated on the basis of the droplet's volume. The volume of a droplet is given by:

$$V_d \quad \frac{D_d^3}{6} \tag{2}$$

Using this equation, it is possible to calculate the volume of each droplet, then the average volume by taking the sum of the volume of all the droplets and dividing it by their number, and then to finally take the cubic root of the averaged volume using equation (2) to get the VMD. The VMD value characterizes the spray by giving the diameter of a hypothetical droplet that has a volume equal to the average volume of all the measured droplets.
Sauter Mean Diameter (SMD) D_{32}: This diameter is calculated using the concept of the volume to surface area ratio. It is equal to the sum of the cube of all diameters divided by the sum of the square of all diameters. This yields a characteristic droplet diameter that has a volume-to-surface-area ratio equal to the volume-to-surface-area ratio of the entire spray. This diameter is particularly important in gas turbine evaporative fogging system applications because the mass transfer happens at the interface of the droplets and the surrounding air (i.e. at the droplet surface). To enhance the evaporation of a population of droplets, one has to maximize the active surface areas and minimize the internal volumes.

Absorption Diameter (AD) D_{21}: This diameter is calculated using the surface to diameter ratio concept. It is equal to the square root of the sum of the square of all the droplets diameters divided their straight sum.
Evaporative Diameter (ED) D_{31}: This diameter is calculated using the volume to diameter concept. It is equal to the sum of the cube of all the droplets diameters divided by their straight sum.
D_{43}, which is the Mean Mass or De Brouckere's or Harden's diameter, used in combustion equilibrium applications.
The following formula may be used to calculate any of the above-cited diameters:

$$D_{pq} = \left(\frac{\sum N_i D_i^p}{\sum N_i D_i^q} \right)^{\frac{1}{(p-q)}}$$

6.0 REPRESENTATIVE DIAMETERS

There are other representative diameters, which can be easily measured from cumulative distribution curves. These are defined as:

***Dv01* (also known as Dv10):** Is a representative diameter where 10% of the total volume of the liquid sprayed is made up of droplets with diameters smaller or equal to the stated value.

***Dv05* (also known as Dv50):** this is the same as the Volume Median Diameter or Mass Median Diameter (MMD), assuming water. This is the representative diameter where 50% of the total volume of the liquid sprayed is made up of droplets with diameters larger than the stated value and 50% is made up of droplets with diameters smaller than the stated value.

***Dv09* (also known as Dv90):** this is the representative diameter where 90% of the total volume of the liquid sprayed is made up of droplets with diameters smaller than or equal to the stated value. This representative diameter is commonly used to characterize gas turbine inlet air fogging nozzles because there is concern that the ingestion of large droplets by the axial flow compressor might cause blade erosion or blade coating wear.

Other median diameters may be used, depending on the application, such as the number median diameter D_{N50} and the surface median diameter D_{S50}.

***RSF* Relative Span Factor:** this is a dimensionless parameter indicative of the uniformity of the drop size distribution. It is given by:

$$RSF = \frac{D_{v09} - D_{v01}}{D_{v05}} \qquad (3)$$

Generally, atomization process leads to the generation of droplets of different size (poly-disperse). Droplets size distribution represents the generated droplets in a sample in range of droplets size.

7.0 DESIGN OF TEST PROCEDURE

Nozzle position: Nozzle should be installed in such a conditions as real installation in gas turbine duct with the same manifold configuration. Typical locations for fogging nozzle installations are either:

Downstream of the air filters

Downstream of the silencers

Located near the bellmouth under special cases.

Flow velocities should be used to match the appropriate location.

Operating pressure: Operating pressure should be specified to optimize the atomizing process for a given optimum design.

Flow Rate: Due to the fact that different nozzle manufacturers have nozzles with different flow rate at a given pressure, nozzle performance should be taken by plotting the curve of droplet diameter versus flow rate for a given pressure. It does not make sense to "compare" nozzle performance with widely differing flow rates hence the approach of plotting the curve stated above helps this analysis.

Nozzle Orifice diameter should be enough small to generate droplet that will evaporate or nearly evaporate before reaching the compressor inlet and enough big to avoid plugging of the nozzle which would result in excessive maintenance and downtime.

Nozzle design: As the individual designs and performance of nozzle vary from manufacturer to manufacturer, the details of the specification should be determined from the supplier.

Location of Measurement: This type of atomization is naturally poly-dispersed, since the response and behavior of big droplets is different from the smallest ones, droplet size is a strong function of the measurement location, and droplet size measurement covering the plume at a given distance from the nozzle orifice and weighted result across the plume is necessary to have more precise and representative droplet size.

Smallest droplet sizes are found in the center of the plume near the exit of the nozzle. The smaller drops evaporate quickly, leaving only the larger droplets as axial distance increases. In the radial direction, droplet size increases as we move to the edge of the plume because the small droplets quickly follow the airflow and move to the center while the larger droplets maintain their initial trajectories and stay in the edge of the plume. To avoid the effect of the disturbance of the evaporation of the smallest droplets on the measurement results, tests should be done in the wind tunnel at near saturation conditions.

Nozzle atomization produce a big number of droplets, the number density of the droplet, and consequently the probability of collision between droplets, is high close to the nozzle tip and decrease with the increase of the distance form the nozzle tip. Nozzles with high flow rate and/or small cone angles have higher collision probability. Consequently, distance of measurement from the nozzle tip should be function of the cone angle and the flow rate.

Filtration: at a given operating pressure, nozzle with smaller orifice generally produce smaller droplets, due to plugging possibility, nozzle orifice has a minimum size, and an appropriate filtration have to be installed immediately upstream of the nozzle inlet, using sub-microns filter or screens.

8.0 TEST CONDITIONS

Conditions that should be applied during the test:

1. Ambient temperature: Ambient temperature should be between 70 and 100F.
2. Relative Humidity: Relative humidity should be close to saturation (90 to 95%).
3. Water Temperature: Water temperature should be between 60 and 90F.
4. Operating pressure: Nozzles should be tested at their design pressure (as defined by the nozzle OEM), provided that this is the pressure utilized in the gas turbine fogging application.
5. Water quality: the water should be demineralized.

9.0 INSTRUMENTATION

Figure one (appendix A), shows the basic test rig design. As shown, it includes:

1. High-pressure pump which may develop up to 3000 psi.
2. Wind Tunnel capable of up to 15 m/s (3000fpm) airflow velocity, Windows has to be made in the wall of the wind tunnel to allow light beam to pass through the spray.
3. Tubing and nozzles. In the experimental setup, flow rate meter, pressure gauge, and control valve should be installed immediately before the testing position.
4. Size measurement systems, different non-intrusive techniques are in use to measure the droplets size as laser light scattering (optical non imaging) systems and video camera (optical imaging) systems.

   There are two techniques that use light scattering principles:

   The spatial technique which instantly sample a large number of droplets in a given volume. A laser beam pass through the fog droplets and detectors installed within the system measure the light scattered by the droplets and derive size information. This is a number-density-weighted technique. Malvern and Imaging Systems are two manufacturers of this type of equipment.

   The flux or temporal technique samples and counts individual droplets passing through the sampling volume in a given time interval and is a number-flux-weighted technique. (PDPA and PMS are tow systems that use this technique).

Video imaging systems (Spatial technique): Conventional imaging system consist of a digital camera to capture frames at a given speed, which is synchronized to pulsed light to freeze droplets in motion, and a computer to analyze the images and display the results. VisiSizer From Oxford Company and Dicam-Pro from the Cooke Corporation are two manufacturers of this type of equipment.

All three techniques in use actually allow real time data acquisition and processing and use mathematical and statistical functions to provide droplet size and size distribution.

The calibration of the used sizing systems (imaging and non imaging) using same samples of known mono-dispersed diameters will determine the level of size resolution and accuracy from each system which will be taken into account when data is to be analyzed using conversion parameters.

Care has to be taken when comparing the test result obtained from each measurement system. Each type of instrument use different optical, electronic, material and different sampling system and consequently different measured type of diameter and the conversion between them may lead to significant difference. The number of variables involved in the production of the liquid droplets may also contribute to variations in the tests results.

The effect of droplet distortion is small due the smallness in size produced by the nozzle, and the use of imaging system will allow to provide the level of this distortion and correct the data.

10.0 TEST PROCEDURE

1. Measurement should be made at flow velocity that is typical for gas turbine inlet duct; typical velocity of flow at the inlet duct is in the 4.6 m/s (15 ft/sec). However, in many gas turbine duct configurations, nozzles manifold has to be installed after the silencer, and in this case the airflow velocity may reach 15.24 m/s (50 ft/sec), consequently, droplet size should be taken at 15, 30 and 50 ft/sec.
2. Airflow should be nearly saturated to avoid evaporation disturbance of the measured diameters.
3. Nozzle should be installed in co-flow position.
4. All tests should be conducted on a minimum of 5 randomly selected nozzles within error bars of 5% on droplet size.
5. Measure across the spray plume at a distance of 2 inches[1] (5 cm) from the orifice.
6. Due to droplets size gradient in the plume, take as many readings as are required to cover the entire cross section of the plume, to ensure obtaining size as representative as possible. This should cover the extreme edge of the plume where droplet of big size are present, and ignoring those droplets may affect greatly the test results and especially D10, diameter measured directly by flux technique.
7. The measurement duration for each portion measured should be a least one-minute, to ensure measurement repeatability. Data will be regarded in this case as time-averaged data.
8. Take flow rate value during the test to insure that orifice is not partially plugged by particles.
9. Take the value of the operating pressure in real time testing.
10. Calculation of the diameter should be a weighted average performed by using the volume concentrations (ppm) derived at each measurement point. This calculation should be done on all representative diameters.
11. Final report should include the Dv90 and D32 (Sauter Mean) diameters, as these are the most significant for gas turbine operations.

11.0 PERFORMANCE CRITERIA

The purpose of atomization is to generate droplets enough small to evaporate or nearly evaporate before reaching the compressor inlet. Using nozzles with relatively small orifice will lead generally to small droplets but with high probability of plugging and relatively high pressure drop due to high nozzle number to be used. Using nozzles with large orifice will lead to big droplet size and consequently less evaporation efficiency a higher probability of compressor blades erosion. Consequently, an engineering compromise should be done when comparing nozzles. The performance of any nozzle is a function of its specific design and

[1] The distance of 2 inches (50.8mm) was been selected, as it is far enough away to allow for the measurement of any coalescence yet close enough to minimize the effect of evaporation, this distance may be increased when the flow rate is high and the cone angle is small or decreased in the opposite conditions.

therefore any comparative testing must be done with the specific design contemplated for use and in taking into account the following issues:

1. Pressure drop and plugging probability when the nozzle orifice is too small, it is not possible to shutdown the plant every few hours or few days to replace the plugged nozzles.
2. Evaporation efficiency, coalescence probability, erosion probability, water pooling, and nozzles distribution efficiency when the nozzle orifice is too big.

For a given nozzle, the following criteria has to met:

Repeatability of the average droplet size is better than 5%.
Average droplet size has to be within 5% of the size stated by the manufacturer.

ASTM Standard E799-92 (1998) "Standard Practice for Determining Data Criteria and Processing for Liquid Drop Size Analysis" may be used as procedures for determining appropriate sample size, size class widths, Characteristic drop sizes, and dispersion measure of drop size distribution. However, the uncertainty level has to be taken into account when conversion between measured data from different techniques is to be done.

12.0 MEASUREMENT RESULTS

Annex B shows example test sheet. Each measurement instrument measure directly specific diameters, in the conversion to D32 and Dv90, the measured diameter has to be specified, as well as the conversion method and the level of measurement error for each instrument.

13.0 ISSUES AND CONCLUSIONS

Several issues that have to be taken in consideration, include the following:

1. The most important quantitative factors for inlet air fogging are the surface area of water exposed for evaporation (affects the evaporative cooling efficiency of the spray) and the size of the largest droplets (affects the potential for compressor blade distress and the amount of water that falls out in the duct). Given the above, the SMD and Dv90 numbers are of primary significance for gas turbine inlet-air cooling. The *location* of the measurement in the spray plume and other measurement conditions such as airflow velocity, are also very important. The importance of considering both SMD and Dv90 when comparing different fogging nozzles suggests the possibility of adopting a single representative diameter that would take both factors into account and would thus be more appropriate for quantifying gas turbine inlet air fogging sprays.

2. Measurement in the spray plume, and other measurement conditions such as airflow velocity, are also very important. Measurements taken in different locations can yield very different results. How to define the distance that a coalescence within a nozzle plume occurs at for example less that 10%/inch?

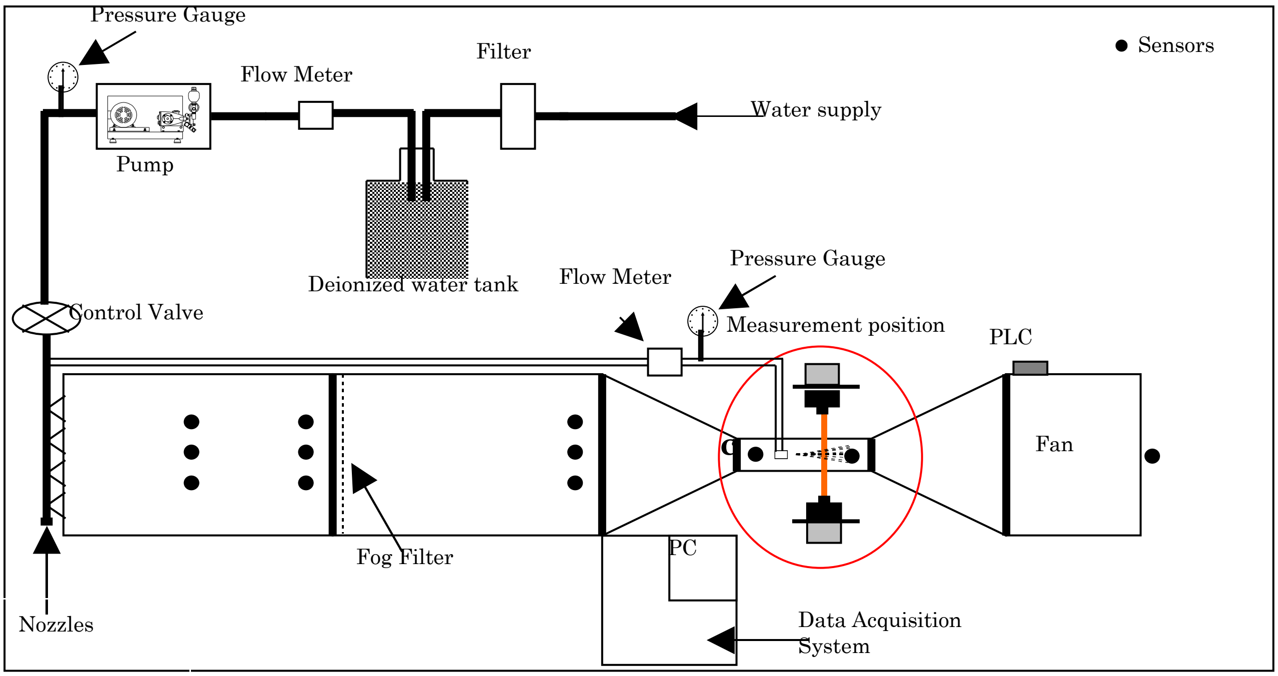
3. Which airflow velocity is to be taken? In gas turbine duct, there is 2 possible positions for the manifold, the first is after the filter house which is the airflow velocity is in the order of 900 fpm, and the second is after the silencer, which is the airflow velocity is in

the order of 2500 fpm. A nozzle with small cone angle and high flow rate, which may make a Dv90 of 25 microns at 2 inches from the nozzle, may have increase in droplets size due to coalescence and Dv90 become 40 microns after 5 inches at 900 fpm, this size may increase to 50 microns when nozzle manifold is installed after the silencer at 2500 fpm.

These issues have to be considered prior to the design of any comparative nozzle test.

APPENDIX A

EXPERIMENTAL SETUP



APPENDIX B

EXAMPLE TEST SHEET

Results of nozzles performance using the testing protocol procedures

Date: January 24, 2007

Name of Company or Laboratory where test performed is performed: --------------
Nozzle manufacturer: ---
Nozzle type: --
Serial number: --
Ambient temperature: ---
Water temperature: --
Instrument of measurement: ---
Calibration precision: ---

N	Time	Operating pressure (psig)	Flow rate (gph)	Airflow velocity (fpm)	Measurement position (R: in; Z: in)	D10 (m)	D30 (m)	D32 (m)	Dv10 (m)	Dv50 (m)	Dv90 (m)	CV (ppm)
1												
2												
3												
4												
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Observations regarding the repeatability, reproducibility and accuracy of the data: