MEASUREMENT OF NOZZLE SPRAY PARAMETERS AND DESIGN OF ONLINE COMPRESSOR WASHING SYSTEM FOR AERO DERIVATIVE INDUSTRIAL GAS TURBINES

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ABSTRACT

This paper presents measurement of spray parameters generated by typical online compressor washing nozzles operated at varying conditions and the design of washing system. Three typical online compressor washing nozzles (N1, N2, and N3) with Equivalent Orifice Diameters (EODs) of 0.38mm, 0.53mm and 0.66mm respectively were selected to ascertain the spray parameters: droplet size and injection flow rate produced at varying injection pressures. A Malvern Spraytec Particle Analyzer and GTMX flow meter were employed to measure the spray droplet size and flow rate respectively. Also, a pressure gauge was employed to measure the pressure of the spray at any given condition. The study demonstrates that droplet size reduced with increased injection pressure, while the injection flow rate increased with injection pressure. Washing system designed with five N2 nozzle which has an Equivalent Orifice Diameter of 0.53mm generates satisfactory water-to-air ratio recommend by original equipment manufacturers for aero derivative gas turbines with less than 50MW of design power output.

Keywords: Droplet Size, Injection Pressure, Injection Flow Rate, Water-to-air Ratio.

INTRODUCTION

Advanced compressor washing techniques such as injection of wash fluid upstream of the compressor blades are used to prevent large build-up of debris on the surfaces of compressor blades. For effective washing of the compressor blades to be achieved, the appropriate spray parameters, namely droplet size, injection flow rate, pressure etc. have to be applied so as the spray injected can penetrate the air stream encountered in gas turbines and wet the blades.
Several authors have given insights on how to obtain an efficient online compressor washing. Mund and Pilidis (2005) stated the entire hub-to-tip of the blade needs to be completely wet with wash fluid to achieve effective washing. Lambart et al. (2003) provided an experimental perspective that the fluid sprayed should completely cover the entire compressor. Hayward et al. (2000) stated that the number of nozzles used should provide effective coverage of spray fluid on the blade surfaces. Lambart et al.(2003) reported droplet sizes of 125-200 for naval application; however, the study stated that the selection of the droplets would depend on the washing system and the gas turbine. Syverud (2007) employed Malvern laser diffraction instrument to measure the droplet sizes generated from a hollow cone and an air assisted flat fan nozzles to analyse their spray characteristics.
Different measurement techniques were used by Khan et al. (2000) to investigate a fan spray nozzle at fixed injection pressure of 8.3bar. The authors observed that there was little or no radial distribution effect on mean droplet size when the injection distance was increased from 25 to 40mm. Jasuja (2008) conducted the measurement droplet sizes generated from two flat

fan nozzles using the Phase Doppler technique. The author reported an increased droplet size with injection distance. Pan et al. (2005) adopted a windowed FFT based approach and an optimized frequency-based algorithm to extract droplet size from a Delavan nozzle.
The study of Syverud (2007) also highlighted the significance of water-to-air ratio in online compressor washing. The authors stated that when a high water-to-air ratio of 3% was employed, both the fourth and sixth stage performances were fully recovered.
Mund and Pilidis (2006) in their study of a numerical survey of influencing parameters of online compressor washing modeled two generic compressor washing systems. Configuration B was reported to have produced a better mixing between the injected fluid and the airflow of the two types of configurations. Fred and Tapparo (1971) patented a removable washing system which consists of four nozzles where the fluid was sprayed into the intake of the compressor airstream. Mansson (1977) Suggested an inter-stage washing system to prevent deposits washed off from front stages re-depositing at the rear stages. A dual purpose system was patented by Fred and Tapparo (1971), which consists of three nozzles where the system was used for both wet compression and online compressor washing
Washing systems have been deployed in cleaning gas turbines without ascertaining the spray parameters which influence the washing effectiveness. For a satisfactory washing to be achieved, washing schemes have to be carefully designed in terms using the appropriate spray parameters such as droplet size, water-to-air ratio, injection pressure etc. (Mund and Pilidis, 2006). This study investigates spray parameters generated from typical online compressor washing nozzles at varying operating conditions with a view to designing a washing system for industrial gas turbines.

METHODOLOGY

Experimental setup

To ascertain the spray parameters: droplet size and injection flow rate produced at varying injection pressures, three typical online compressor washing nozzles (N1, N2, and N3) with Equivalent Orifice Diameters (EODs) of 0.38mm, 0.53mm and 0.66mm respectively were selected (see Veejet Flat Spray performance data, 2010). Malvern Spraytec Particle Analyzer and GTMX flow meter were employed to measure the spray droplet and flow rate respectively. Figures 1and 2 show the Spraytec particle analyzer and GTMX flow meter respectively. Also, a pressure gauge shown left of Figure 2 was employed to measure pressure of the spray at any given condition. The Spraytec particle analyzer employed to measure the droplet size of the nozzle under different operating conditions, uses laser diffraction method. The equipment utilizes angular intensity scattered light to measure droplets when a spray passed through the laser beam. The appropriate optical model is then used to analyze the scattered light pattern recorded to yield a size distribution

Figure1: Malvern Spraytec Particle Analyzer(Courtesy Malvern Instrument Ltd, 2007)

Figure 2: Pressure Gauge and GTMX flow Meter

Two separate and independent traverse systems were employed to enable adjustment of the nozzle to the appropriate position relative to measurement region where the beam passes through. One of the traverse systems is attached to the bed where the Spraytec is mounted, to facilitate movement of the Spraytec; while the other is attached to the nozzle to allow adjustment of the nozzle positioning in three degrees of freedom (see Figure 3). With the combination of these two traverse systems, the measurement of the spray could be carried out at different sections and distances of the spray.

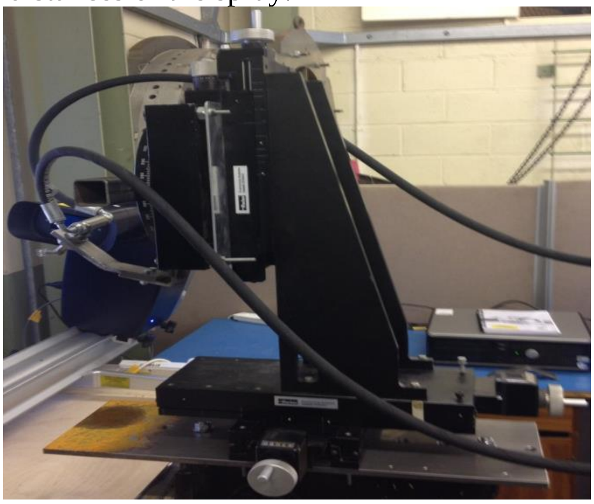

Figure 3: Injector Unit (Traverse gear)

Also, an injector system which comprises high pressure piston pump and tank shown in Figure 4, and a mechanical traverse unit where the nozzle is attached (see Figures 3), was used to inject the wash fluid. The tank is capable of containing 40litres of wash fluid and it has a heat coil that can be used for heating the wash fluid before being injected. A piston pump of 5.5 Hp, driven by a 2.2KW electric motor which runs at 1128rpm was used to inject the wash fluid from the tank through the nozzle tip at high pressures. A knob in the control panel was used to regulate the pressure at which the fluid is being injected. Figure 5 shows the control panel for the washing system.


Figure 4: Injector System: Piston Pump and Tank


Figure 5: Injector System Control Panel

In this study, wash fluid injection pressure was varied from 10 to 90bar to investigate its influence on droplet size. A range of 10 to 90bar injection pressure was considered to account for low and high injection pressures associated with compressor washing. Mund and Pilidis (2006) stated that pressures of 50bar and above are termed as high injection pressures while the pressures below 10bar are referred as low injection pressures.

As mentioned earlier, the injection pressure was varied from10 to 90bar separately for the three nozzles; each sampling lasted for about 30 seconds. Consequently, the results from the measured spray droplets were averaged in the Malvern Spratec software. Figure 6 shows the spray injected across the beam to measure the droplet size. Injection flow rate and pressure for the varying operating condition were read directly from the GTMX flow meter and pressure gauge displayed in Figure 2. Similar to the droplet size measurements, the flow rate readings were obtained by varying the injection pressures from 10 to 90bar for the different nozzles.

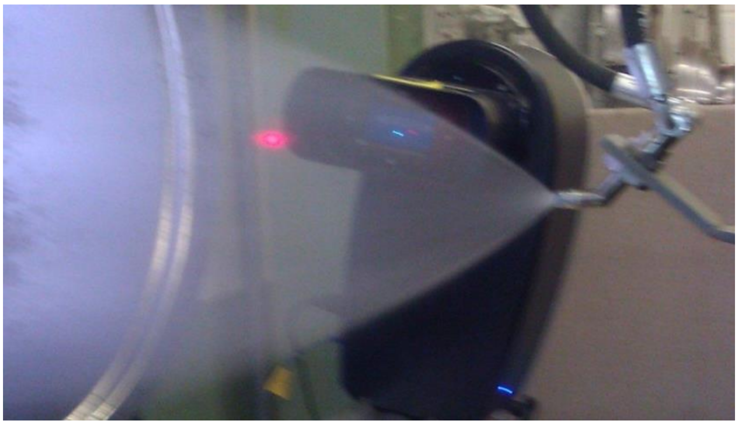

Figure 6: Droplet Sizing using Malvern Spraytec Particle Analyzer

Injection distance was varied from 50 to 200mm, in steps of 50mm to ascertain its effect on the spray droplet sizes and injection flow rate. The injection distance considered herein could be related to the distance from the nozzle position at the inlet of the tunnel to the cascade blades
Droplet size and injection flow rate data obtained from the spray analysis of nozzles, were used to design the washing system. Syverud (2007) stated that the effectiveness of online compressor washing system is influenced by water-to-air ratio, droplet size, injection pressure, spray pattern etc.
In this study, based on the suggestions made by Syverud (2007), spray injection pressure, water-to-air ratio, droplet size were considered when designing the online compressor washing system for an aero derivative gas turbine. Details of specification are:

1. Water to air ratio of 0.46% was adopted
2. 62litres was adopted as the quantity of wash fluid used per wash (Courtesy R-MC Power recovery Ltd)
3. High injection pressure of 90bar was considered
4. Twin shaft aero derivative gas turbine with a design power output of 25MW and mass flow rate 70kg/s was adopted

In this study, online washing system was designed for an aero derivative gas turbine derived from LM2500 GE class of engines based on the quantity fluid per wash specified by R-MC Power recovery Ltd and the recommendations by Syverud (2007) which suggested a water-to-air ratio of 0.46 for washing systems employed in twin shaft aero derivatives engines. Also, wash duration of 3 minutes was considered. The calculations were carried out using Microsoft excel to ascertain the numbers of nozzles for the washing system.
To design the washing system, one out of the three nozzles, N2 Nozzle, which produced satisfactory water-to-air ratio recommended, was used to design washing for the aero derivative industrial gas turbine.

RESULTS AND DISCUSSION

Droplet size Measurement Analysis

Figure 7 shows the droplets generated for varying injection pressures. As can be seen, with reference to N2 nozzle, droplet size reduced from 128.8µm to 78.6µm when injection pressure was increased from 10 to 90bar. These mean droplet size values fall within range of droplet sizes recommended for online washing. Lambart et al.(2003) reported droplets of 125-200µm for online compressor washing. Similarly, Patterson and Spring (1992) suggested droplet sizes of 80-200µm for naval application. The reduction in droplet size can be attributed to increased velocity as a result of the increased pressure, thereby resulting in finer atomized droplet sizes. Also, since injection pressure increases with velocity, when injection velocity is increased, the liquid sheet that emanates from nozzle tip disintegrates earlier which results in the formation of ligaments close to the nozzle exit; hence finer droplets are generated when compared with lower injection pressure spray.

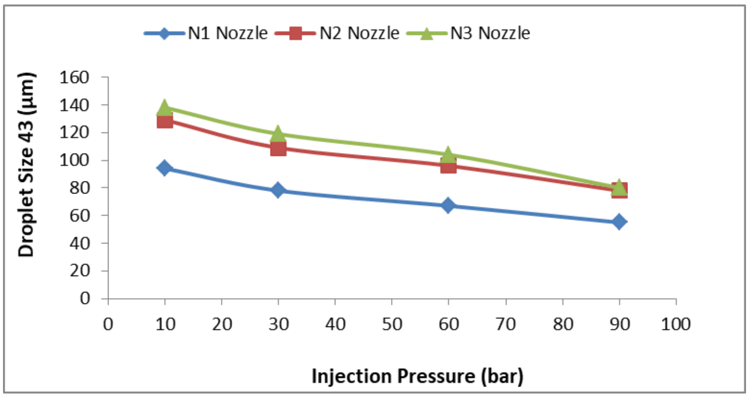

Figure 7: Droplet size variation with injection pressure

The cumulative distribution curves for the three nozzles follow similar pattern under varying injection pressures. Therefore, it is only cumulative distribution plots for N3 nozzle that is presented in Figure 8, to demonstrate the effects injection pressure on mean droplet size. As can be seen from the figure, when the cumulative distribution plots of the different injection pressures were compared at 50%, the particle diameter for 10bar produced the largest droplet size, while 90bar generated the smallest particle size of droplet.

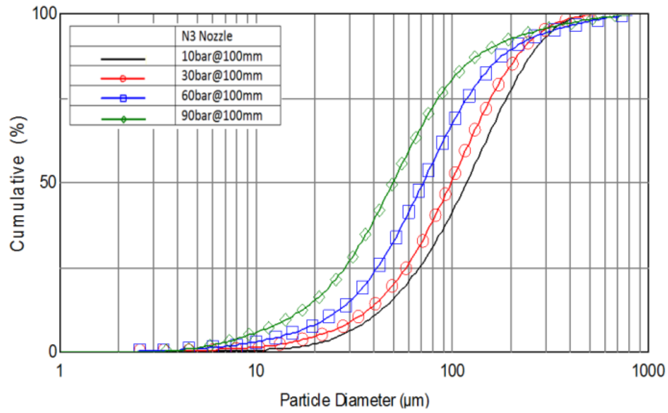

Figure 8: Cumulative Distribution curves for N3 at varying Injection Pressures

Table 1: Droplet sizes at varying injection pressure

Injection Pressure	N1 Nozzle	N2 Nozzle	N3 Nozzle
10bar	93.9µm	128.8 µm	138µm
30bar	79.6µm	109.1µm	119µm
60bar	67.4µm	95.6µm	104.4µm
90bar	55.1µm	78.63µm	80.24µm

Also, when injection distance from tip of nozzle to measurement region was increased, the plots show that the droplet size reduced with increased injection distance (see figure 9). This reduction in droplet size with increased injection distance could be caused by disintegration or breakup of the spray as it travels farther away from the nozzle tip; thereby, resulting in finer droplets. These findings contradict the study of Jasuja (2008) which state that droplet sizes increase with injection distance. The study attributes the increase in droplet with distance, to a secondary process of droplets collision and coalescence owing to high density environment. In addition, the measurements were carried out at high pressure controlled condition. In this study however, the droplets measured at ambient conditions.

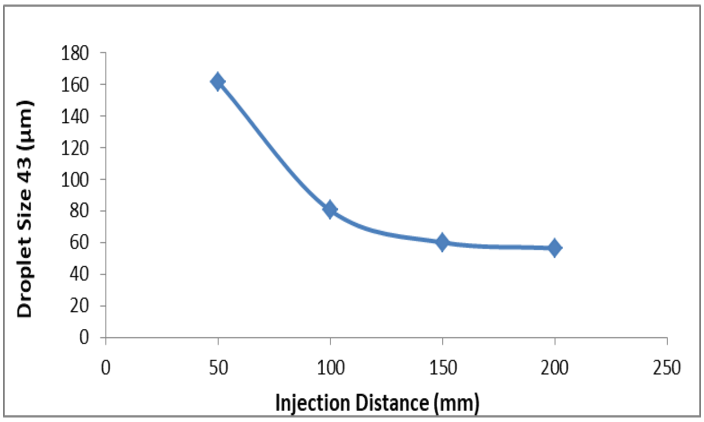

Figure 9: Droplet size variations with injection distance

The cumulative distribution curves at varying injection distances are shown in Figure 10. At 50% cumulative distribution, the plots show that injection distance of 50mm produced largest droplet particle size diameter, while injection distance of 200mm generates the smallest particle diameter of droplet.

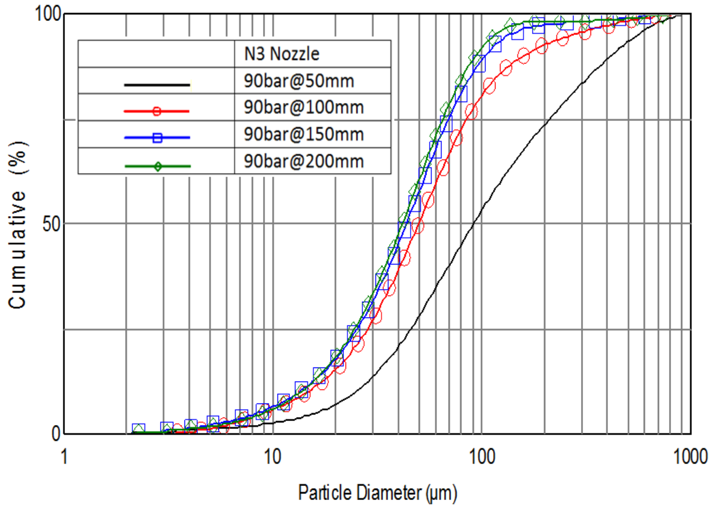

Figure 10: Cumulative distribution curves for varying injection distance

Fluid Injection Flow Rate Measurement Analysis

Figure 11 shows the plot of injection flow rate against pressure. As can be seen from the figure, injection flow rate increased with pressure. Also, from the figure, it obvious that at 10bar injection pressure, the injection flow rate is zero. This can be attributed to low level of flow rate, thereby making it impossible for the flow meter to read any value of flow at that injection pressure. Figure 12 shows the plots of injection flow at 90bar injection pressure against equivalent orifice diameter. The figure shows that the fluid injection flow rate increased with orifice diameter.

Table 2: Flow rates at varying injection pressure

Injection Pressure	Nozzle N1(kg/min)	Nozzle N2(kg/min)	Nozzle N3(kg/min)
10bar	nil	nil	nil
30bar	nil	0.62	1.14
60bar	nil	1.05	1.62
90bar	0.36	1.36	2.13

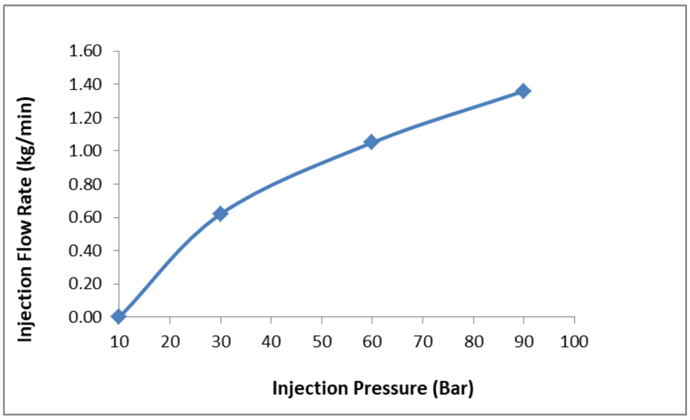

Figure 11: Fluid injection flow rate against pressure

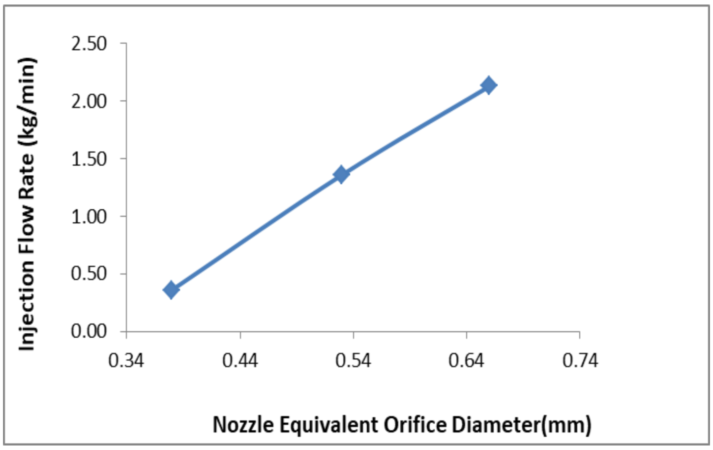

Figure 12: Fluid injection flow rate against orifice diameter

When water-to-air ratio was plotted against number of nozzles for the three nozzles, it was observed that when five N2 nozzles were used, it generated water-to-air ratio of 0.48, which is in proximity with water-to-air ratio specified by Syverud (2007). Also, the plots show that three N3 nozzles produced water to air ratio of 0.45, which close to the water-to-air ratio specified in the literature. However, N3 nozzle was not considered for the washing system design because three nozzles only may not provide the spray coverage of the entire blades in the gas turbine compressor.

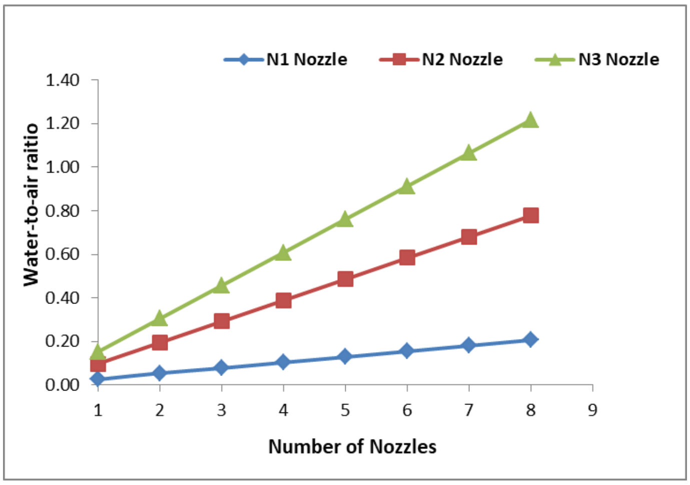

Figure 13: Water-to-air Ratio against number of nozzles

Design of Online Washing System

Based on the outcome of the water-to-air ratio investigation, it was only N2 nozzle that was considered for the design of online compressor washing system for the aero derivative gas turbine.

Figure 14 shows the plots of fluid injection flow rate generated for different washing system systems. The figure shows that washing system designed with nozzles having orifice diameter of 0.38mm produced an injection flow rate of 0.15kg/s when five nozzles were used, as against 0.34kg/s and 0.53kg/s for washing systems with nozzle equivalent orifice diameter of 53mm and0.66mm respectively. Similarly, Figure 14 shows the plots of water-to-air ratio for washing systems with different nozzles. The plots show that water-to-air ratio generated by the washing system which is made up of nozzles with orifice diameter of 0.38mm generates a water-to-air ratio of 0.36% as against 0.48 and 0.76 % for washing systems with orifice diameter 0.53mm and 0.66mm respectively. From the foregoing, it is obvious that washing systems with nozzles having orifice diameter of 0.38mm falls short of the water-to-air ratio specified by Syverud (2007), while the one with orifice diameter of 0.66mm exceeds the specified ratio. Washing system having nozzle with orifice diameter of 0.53mm generates 0.48% which is in proximity with the specified water-to-air ratio of 0.46 for aero derivative engines with less than 50MW. According Syverud (2007) using low water-to-air ratio for washing could impair the effectiveness of the washing, while the other hand, if the water-to-air ratio is too high, it could cause secondary damage such as erosion of the blade surfaces.

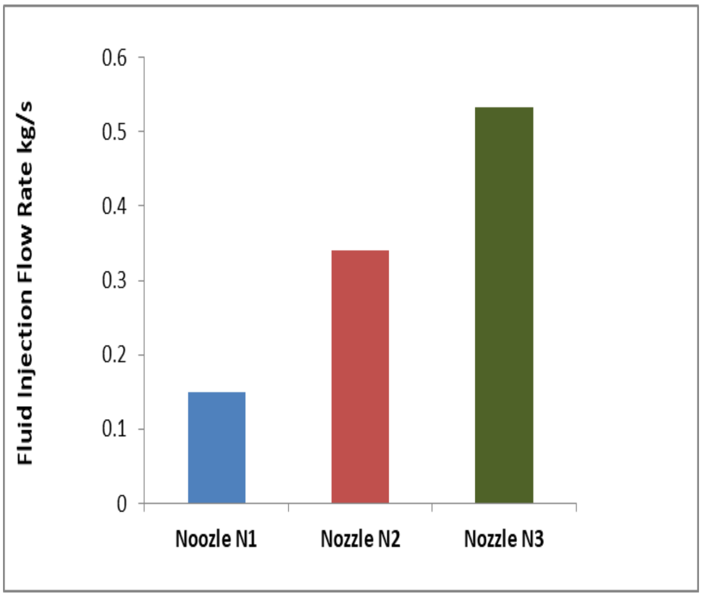

Figure 14: Fluid injection flow rate for washing systems with different nozzles

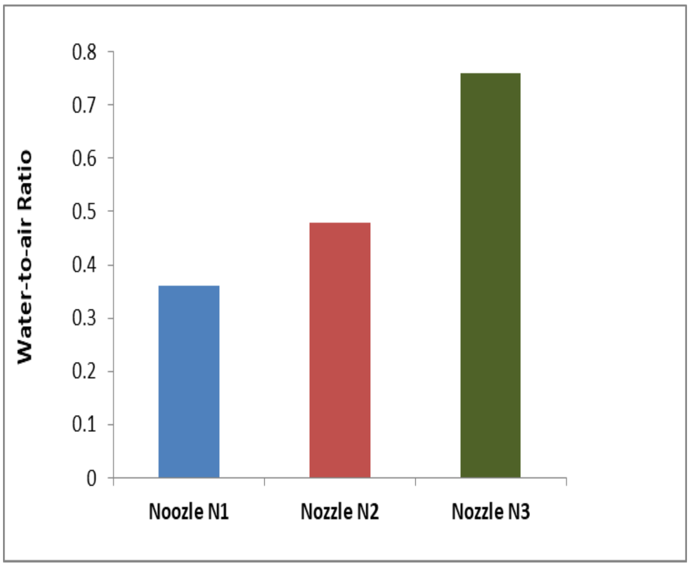

Figure 11: Water-to-air for washing systems with different nozzles

CONCLUSIONS

This paper presents measurement of spray parameters generated by typical online compressor washing nozzles operated at varying conditions and the design of washing system. Three elliptical fan nozzles were selected, followed by using Malvern Spraytec Particle Analyser and GTMX flow meter to obtain the droplet sizes and injection flow rates generated at varying operating conditions. The outcomes drawn from the investigation are:

1. The study highlights that droplet size reduces with injection pressure and distance
2. Fluid injection flow rate increased with injection pressure and nozzle equivalent orifice diameter
3. Washing system which comprised Nozzle with Equivalent Orifice Diameter of 0.53mm generates a satisfactory water-to-air ratio recommend by original equipment manufacturers for aero derivative gas turbines with less than 50MW of design power output.

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REFERENCES

Mund, F. C. and Pilidis, P. (2005), "Online compressor washing: A numerical survey of influencing parameters", Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol. 219, no. 1, pp.13-23.

Lambart, P., Gordon, R. and Burnett, M. (2003), "Developments in on-line gas turbine compressor cleaning", Proceedings of the Institution of Diesel and Gas Turbine Engineers 2nd Gas Turbine Conference 2003, 7-8 October 2003, Milton Keynes, UK, pp. 136-142.

Hayward, J.,Winson, G., Raatre,A. (2000) Wash system for gas turbine compressors. Speciality in Chemical holding. Patent no. US Pat.6 073 637. (Accessed: 13 June 2000) .

Syverud, E. (2007), Axial compressor performance deterioration and recovery through online washing (PhD thesis), Norwegian University of Science and Technology.

Khan, A., Hyde M. G. and Jasuja A. K. (2000), "Investigation into the behaviour of fan spray using LSI/PDPA/PIV techniques", ILASS-Europe 2000, 11-13 September 2000.

Mund, F. C. and Pilidis, P. (2005), "Online compressor washing: A numerical survey of influencing parameters", Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, vol. 219, no. 1, pp. 13-23.

Mansson, M. (1977), Washing Apparatus for Compound Compressor. US patent 4046155.

Freid, W. B. and Tapparo, D. J. (1971), "Wash manifold" US patent No.3623668.

Jasuja A. K. (2008), "Structure of high throughput, dense pressure atomized elliptical sprays under high ambient air pressure conditions", ILASS-Europe 2008, 8-10 September 2008.

Pan, G., Shakal, J., Lai, W., Calabria, R., Massoli, P. and Pust, O. (2005), "Simultaneous global size and velocity measurement of droplets and sprays", Proceedings of the 20th ILASS—Europe Meeting.

Veejet Flat Spray Nozzles Performance Data, www.spray.com (accessed 26 June 2010).

Malvern Instrument Ltd. Available at: http://websrv.mece.ualberta.ca/intranet/public.php/research_inventory/display_research_inventory_file/id/92 (Accessed: 15 December 2011).

Patterson, J. S. and Spring, S. K. (1992), ""On-Line Detergent Washing: Reducing the Environmental Effects on the LCAC Gas Turbine Engines"", On-Line Detergent Washing: Reducing the Environmental Effects on the LCAC Gas Turbine Engines, .

ISSN 2056-5860

Asplund, P. (1997), "Gas turbine cleaning upgrade (compressor wash)", Proceedings of the 1997 ASME ASIA Congress & Exhibition, 30 September - 2 October 1997, Singapore, ASME, New York, .