IMPACTION PIN ANGLE AND NOZZLE ORIFICE DIMENSION DESIGN EFFECTS IN SPRAY PATTERNS FOR GAS TURBINE INLET COOLING

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ABSTRACT

Inlet air-cooling using impaction pin nozzles is one of the cost-effective methods that can be installed at Power Plant Gas Turbines to enhance the power output and thermal efficiency. The performance of inlet air-cooling is highly dependent on the nozzle type and the spray droplet size. This paper investigates the effect of impaction pin angle and nozzle orifice diameter on SMD and spray angle used in inlet fogging systems. Besides that, it also investigates the effects of water flow rate. A test-rig system has been used to produce spray from an impaction pin nozzle. The resultant sprays produced are then captured by using a Complementary Metal-Oxide-semiconductor (CMOS) sensor camera with 16.2 million pixels resolutions. Spray characteristics such as spray angle and spray Sauter Mean Diameter (SMD) has been analyzed and determined eventually. The experimental results show that the SMD value is highly dependent on the flow's Reynolds number and impaction pins angle as higher Reynolds number and smaller impaction pin angle decreases the spray SMD value for both 1.0 mm and 1.5 mm orifice impaction pin. In addition, impaction pin angle also affects the spray angle and it is found that lower impaction pin angle which is 30° produces the biggest spray angle for 1.0 mm (97.40°) and 1.5 mm (65.50°) diameter orifice impaction pin.

Key words: Impaction pin; nozzle orifice; gas turbine

INTRODUCTION

Inlet air-cooling is one of the economical ways to enhance the power output and thermal efficiency of Power Plant gas turbines (Zainali et al., 2015). It was shown that when the inlet temperature decrease, the capacity increase with reduced heat rate. There are a lot of cooling techniques available for industrial gas turbines, and one of it is using the method of inlet fogging (Kakaras et al., 2006). This method uses the application of water sprayed directly at the compressor intake and thus, cooling the air. (Ameri et al, 2004) reported that the nozzle type and droplet size will affect the performance of gas turbine engines when they conducted a study using and generating water droplets with diameters ranging between 10 and 40 μm at pressures above 70 bars with fog nozzles injecting water (Ameri et al, 2004).

The inlet fogging enhancement is a complex process because it depends on various factors. Results produced by (Chaker et al, 2002 & 2004) as shown in their several reports had explained in detail the thermodynamics, heat transfer, size analysis, nozzle types, air inlet ducts fog behaviour, computational fluid dynamics numerical analysis, and wind tunnel testing. When water is sprayed using the fog spray nozzles, every second were producing billions of droplets. The droplet evaporation time is proportionate with the volume-to-surface-area ratio and the water should be broken into smaller droplets so that the water surface area exposed to the air is larger and the smaller droplets evaporate faster than larger droplets.

Research had discovered that the inlet fogging droplets maximum limit to fully evaporate is not bigger than 20-microns in one to two seconds they spend in the inlet airflow. To achieve this standard, the impaction pin nozzle must be properly designed (Mee Thomas, 2011). Larger droplets are harder to evaporate and not able to follow the airflow around obstructions such as inlet silencer panels and duct support structures. More likely the droplets will be collected on duct obstructions and settle on the duct floor (Mee Thomas, 2011). An accumulation of water will occur when fog droplets impact on duct support struts. Flowing and pooling water will be created on the inlet duct walls or floor when droplets impact on silencer panels or duct walls. Large droplets or pooled water will cause compressor blade erosion if have been suctioned into the compressor inlet (Mee Thomas, 2011). The design of the fogging system and the control system must be considered with the factor of compressor inlet temperature distortion and rate of change. The issue of surge margin for each specific engine type must be evaluated. The factors that would impact the surge margin including blade condition and the presence of severe compressor fouling must be evaluated as well (Mustapha et al, 2006).

Impaction-pin nozzles and swirl-jet nozzles are two types of nozzles that are commonly used for inlet fogging. These two nozzles designs operate on the principle of converting high water pressure into increased velocity as water passes through a tiny nozzle orifice. As water exits the nozzle orifice, it forms a conical sheet of water that gets ever thinner the farther it moves from the orifice. Surface tension causes the cone to first break down into fingers of water, and eventually, air instability breaks these fingers down into minute droplets for fast and efficient evaporation. This study focuses on impaction-pin nozzles because impaction pin nozzles produced droplet sizes less than half the size of those produced by the swirl-jet nozzles, indicating that fog produced by impaction-pin nozzles will evaporate more completely and will contain fewer large droplets that can damage the Gas Turbine Compressor (Sun et al, 2020, Rogers Kerry, 2011). Impaction pin nozzles consist of a smooth, short, straight-through orifice with a specially engineered impaction pin in front of the orifice. When a fine jet of water is emitted, which immediately strikes the pin, the water will form a cone of micro-fine particles (Rogers Kerry, 2011). Different nozzle design may produce different droplet distribution. Thus, the characteristics of the nozzle can influence gas turbine performance (Kumar et al, 2015).

Measurement of the droplet size for impaction pin nozzles has been found in several published papers (Kumar et al, 2015, Chaker et al, 2007, Chaker et al, 2003, Chidambaram et al, 2018 & Suryan et al, 2011). Unfortunately, papers that exist in the open literature which provide the effect of impaction pin design on the droplet produced by the nozzles is hard to be found. Even though there are various dimensionless number used to provide insight to the droplets produced by nozzles such as Weber number (Guildenbecher et al, 2009) and Reynolds number (Omer, K., & Ashgriz, N. ,2011), there are very few of them that explore about impaction pins properties and design (Sun et al, 2020). Besides that, most correlations available from previous studies are suitable for a specific nozzle, and the effect of a unique nozzle structure such as impaction pin nozzles is rarely discussed (Sun et al, 2020, Kang et al, 2018, Chaker et al, 2007). Thus, this study intends to check the difference of the droplets Sauter Mean Diameter (SMD) and spray angle produced when the impaction angle is varied to 30°,60°, and 90°. SMD is an important indicator to evaluate the atomization characteristics and performance of nozzles. Besides that, the effects of water flow rate when impacted to 30°, 60°, and 90° impact pin were also investigated.

RESEARCH METHODOLOGY

Impaction pin geometries and operating principles

The investigated impaction pin atomizer consists of a replaceable impaction pin with different pin angles as per Figure 1, α. The impaction pin was designed on a plate together with a variable orifice diameter angle as per Figure 1, β. The water jet discharged from the orifice impacted the pin resulted in the formation of a conical shape thin sheet. The conical water sheet becomes thinner as it travels further downstream. The primary breakup mainly due to the high operating pressure and impaction. Secondary breakup is the influence of aerodynamic and surface tension that breaks the sheet into droplets.

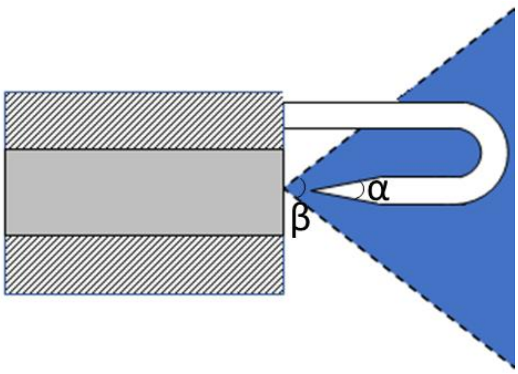

Figure 1. Impaction pin with pin angle, α, spray angle, β, and orifice diameter, d

Experimental test-rig and data acquisition

An experimental test-rig platform for the atomizer performance test was built as per Figure. 2. The system consisted of a centrifugal pump to deliver pressurised water from the supply tank to the atomizer. Ball valve was placed at the pump outlet to control the amount of water flowing. The water flow rates were obtained from the water flow sensor. A water strainer was installed before the water flow transmitter inlet to prevent dirt or debris from passing through and damage the sensor. Water operating pressures were measured using a digital pressure gauge. The impaction pin atomizer was positioned vertically downward and water was sprayed into a water collection tank. The spray images produced were taken by using a Complementary Metal-Oxide-Semiconductor

(CMOS) sensor camera with 16.2 million pixels resolutions. The speedlight was set to a maximum value in an exposure of 26µs. Shadowgraph method was used to obtain the spray image results. Data acquisition method for the spray angle was explained in (Ghaffar et al, 2014) and droplet sizing was based on (Ali Asgarian et al, 2020) technique.

Experimentation

The investigation on the impaction pin atomization mechanics involved the effect of internal flow Reynolds number, Re and impaction pin angle on both spray angle and Sauter mean diameter, SMD. The change of impaction pin angle was performed by replacing the impaction pin. The Reynolds number was varied with different orifice diameters. Reynolds number is defined as:

$$Re = \frac{\rho V d_o}{\mu}$$

Where;

ρ = water density (kg/m3)

V = water velocity (m/s)

µ = water viscosity (N.s/m2)

do = orifice diameter (m)

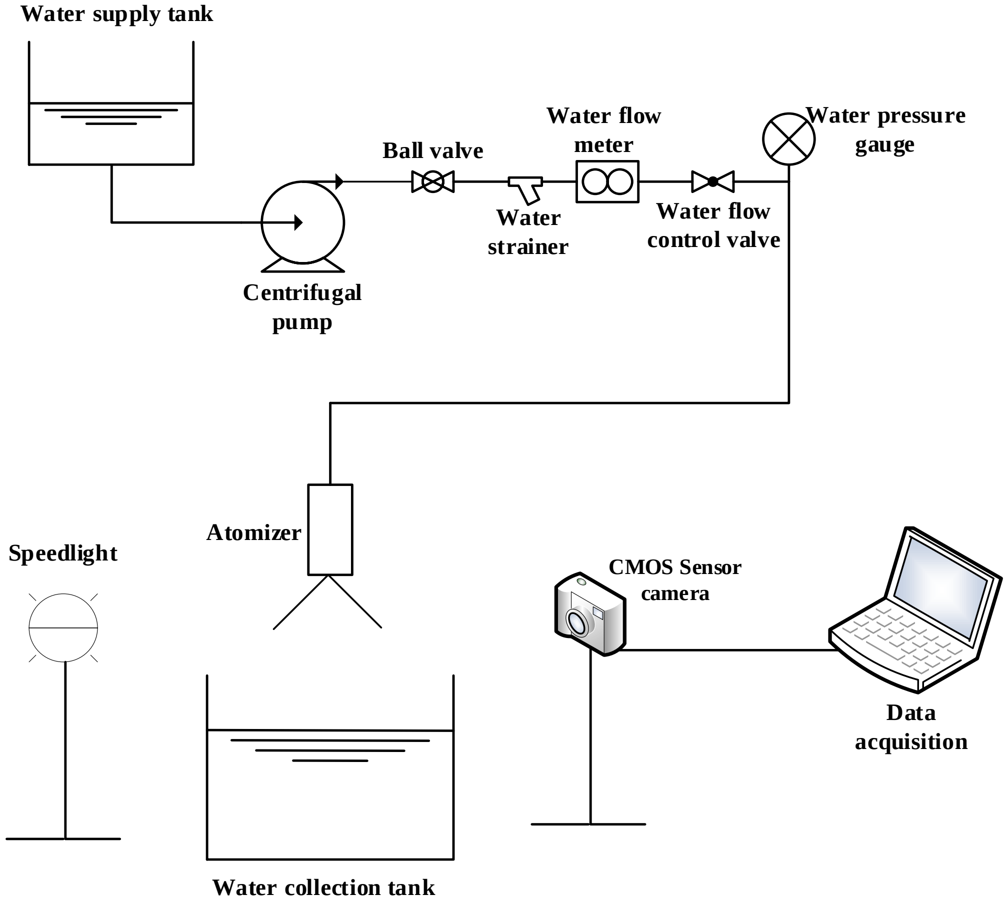

Figure 2: Line diagram of experimental test-rig

Experimental condition

The working fluid used in this study is water at 20 °C with water density, ρwater = 998 kg/m3 and viscosity, µwater = 0.001 N·s/m^2. The nozzle orifice size, impaction pin angle and flow (LPM) settings for the experiment is shown in Table 1 below. Reynolds number is calculated using equation 1 to show the flow regimes of spray produced by the nozzles. The flow LPM was selected so that three types of flow regimes can be tested for this experiment which are transitional, turbulence and higher turbulence as shown in Table 2.

Table 1. Nozzle orifice diameter, Impaction pin angle (°) and Flow (LPM) settings for experiment

Orifice diameter, d (mm)	Pin Angle, α (°)	Flow (LPM)
1	30	0.1
1	30	0.2
1	30	0.3
1	60	0.1
1	60	0.2
1	60	0.3
1	90	0.1
1	90	0.2
1	90	0.3
1.5	30	0.2
1.5	30	0.3
1.5	30	0.4
1.5	60	0.2
1.5	60	0.3
1.5	60	0.4
1.5	90	0.2
1.5	90	0.3
1.5	90	0.4

Table 2. Reynolds number and Flow regimes of the nozzle settings selected

Orifice (mm)	Flow (LPM)	Reynolds No.	Flow Regimes
1	0.1	2118	Transition
1	0.2	4236	Turbulence
1	0.3	6354	Higher Turbulence
1.5	0.2	2824	Transition
1.5	0.3	4236	Turbulence
1.5	0.4	5648	Higher Turbulence

RESULTS AND DISCUSSIONS

The effects of impaction pin angle and Reynolds Number on SMD results

Figure 3 and Figure 4 show the results of SMD produced by 1.0 mm and 1.5 mm orifice impaction pin nozzle using three different Reynolds number impacted on a 30°, 60° and 90° impact pins. Figure 3 and 4 compare the Reynolds number with the Sauter mean diameter produced by the nozzles. The Reynolds number is chosen because it is the ratio of inertial force to viscous force and a higher Reynolds number indicates that the flow is having a stronger inertial force than fluid viscosity. The inertial forces for break up affect nozzle atomization and the viscous force resists the breaking of the liquid film (Adheena et al., 2018).

It is clear from both results that an increase in the flow rate which is represented by the Reynolds number decreased the SMD value for every pin angle tested for both 1.0mm orifice and 1.5 mm orifice nozzles. This result agrees with what is reported by Adheena et al. (Adheena et al., 2018). When the SMD value decreases, it increases the fluid surface area, and speeds up droplet's formation, and expands the spray angle, as shown in Figure 5. The low value of SMD obtained at a higher Reynolds number indicates the higher surface area, hence improve the evaporation of the impaction pin nozzle injector and consequently more overall cooling (Sun et al., 2017). However, even though increasing the flow rate is known to promote lower SMD, it is not preferable as it is not an economical approach (Salman et al., 2019).

Both results from Figure 3 and 4 show that the optimum value of SMD which is the lowest value can be obtained using flows with higher Reynolds number. In this case, flows in the highly turbulent flow compared to transitional or turbulence flow. The results further showed that the SMD value is highly dependent on the impaction pins angle within the investigated range of Reynolds number.

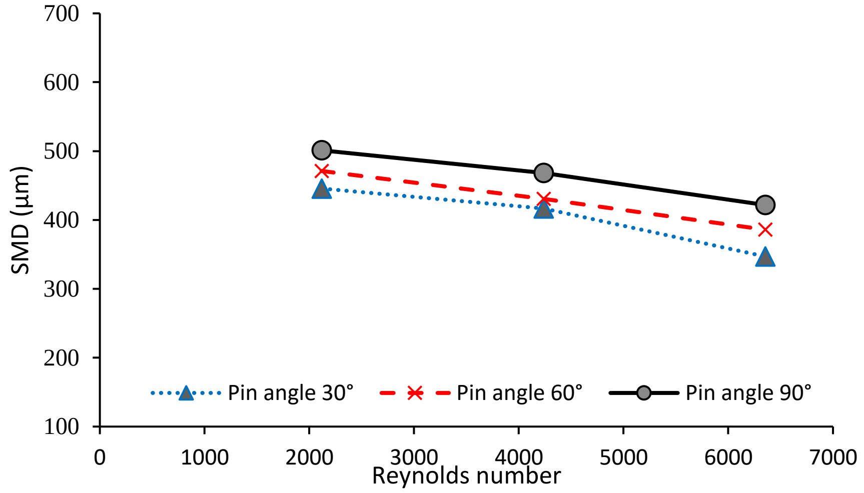

Figure 3. Sauter Mean Diameter (SMD) values obtained from 1.0 mm nozzle with 30°, 60° and 90° impaction pin nozzle spray

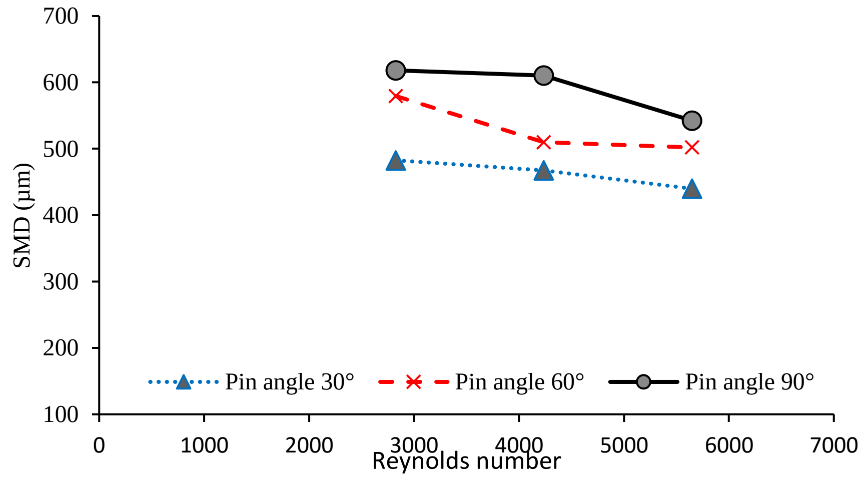

Figure 4. Sauter Mean Diameter (SMD) values obtained from 1.5 mm nozzle with 30°, 60° and 90° impaction pin nozzle spray

The effects of impaction pin angle and Reynolds Number on spray angle

Spray angle refers to the angle formed by the boundaries of the area that is occupied by the water mist from the breakup of the impaction pin and is used to determine the coverage surface area (Sapit et al., 2019). Figure 5 shows the results of spray angles produced by 1.0 mm and 1.5 mm orifice impaction pin nozzle using three different impaction pins of 30°, 60° and 90°. It is clear from the figure that nozzles with lower impaction pin angle produce the widest spray angle thus can cover more surface for cooling purpose.

For 1.5mm orifice nozzle, it can be seen that the increase on impaction pin angle only decrease the spray angle until 60° and an increase in Reynolds Number had increased the spray angle for every pin angle tested. It is also observed that the increase in the impaction pin angles and orifice size decreases the spray angle for 1.0 mm and 1.5 mm orifice impaction pin. When the impaction pin orifice diameter was changed to 1.5 mm, it is found that the increase of Reynolds number also increases the spray angles slightly. Similar to the 1.0 mm orifice results, it can also be said that the increase in the value of the pin angle increases the spray angle.

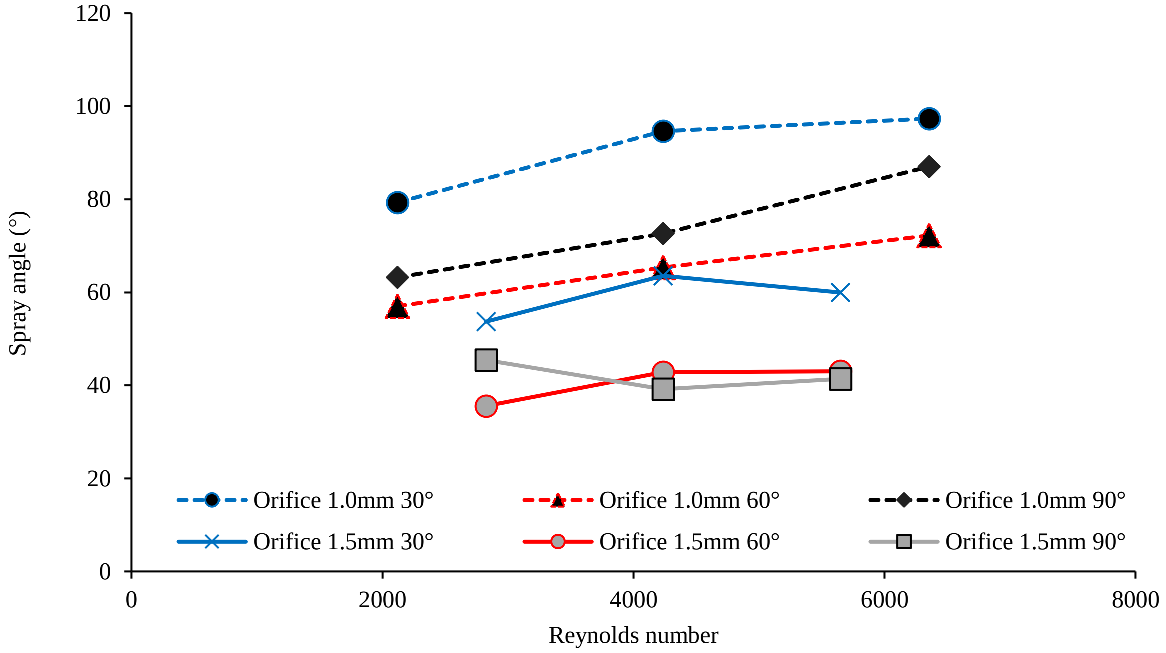

Figure 5. Spray angle produced for each 1.0 mm (dashed lines) and 1.5 mm (solid lines) orifice nozzles with 30°, 60° and 90° impaction pins

CONCLUSIONS

In this paper, a study has been conducted to investigate the behaviour of spray angle and droplet size caused by 1.0 mm and 1.5 mm nozzle orifice impaction pin nozzle together with nozzle impaction pin angle of 30°, 60° and 90°. The main conclusions from this study are:

i. Smaller orifice size, smaller pin angle and high Reynolds number is a major factor contributing to smaller droplets size.
ii. Nozzle orifice is found affecting the spray angle as well. The smaller orifice produces a relatively wider spray angle than its larger counterparts due to higher back pressure when using small orifice.
iii. The orifice size, pin angle and Reynolds number will affect the spray water angle and droplets size. Smaller pin angle coupled with small orifice size with high Reynolds will produce large spray angle. This is due to the smaller diversion of the pin which changes better flow direction.

Overall, the nozzle geometry and other specific features to the application will vary the spray optimization parameters. The analytical method and the nozzle testing set proposed in this study can be used as a reference to gain optimum solution for nozzle application in a Gas Turbine inlet cooling system and to get a complete evaporation process of water droplets. There may be some possible limitations in this study such as possible errors occurring in the experiment test-rig instruments and data measurements. Such errors were minimized by conducting double-check before the test were carried out and also during data entry. Future study should pave ways into the performance of the spray cooling using impaction pin nozzles. In addition, integration of inlet air cooling using impaction pin nozzles with optimized orifice size and pin angle can improve the spray distribution and consequently the performance of the industrial gas turbine especially in hot climate conditions such as in the Southeast Asian countries. This paper provides significant knowledge by proposing that the use of smaller orifice size and impaction pin angle can enhance the Gas Turbine Inlet fogging cooling performance in view of smaller droplets size and widest spray angle.

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