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CFD Modelling of a Water-Jet Cleaning Process for Concentrated Solar Thermal (CST) Systems

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ABSTRACT

In this paper we have undertaken an in-depth analysis of water-jet cleaning process for concentrated solar thermal (CST) systems by fluid dynamics simulations. The heliostat surface cleaning efficiency as a function of machine parameters such as nozzle diameter, jet impingement angle, standoff distance, water velocity and nozzle pressure has been modelled with ANSYS CFX software.
The scope is to develop an optimized cleaning procedure suitable for CST plants through the correlation between main technical parameters, as described above, and the generated shear stresses on the heliostats surface. In this analysis, shear forces represent the “critical phenomena” at the bottom of soil removal process. Enhancing shear forces on a particular area of the target surface, varying the angle of impingement in combination with the variation of standoff distances, can increase cleaning efficiency. This procedure intends to improve the cleaning operation for CST mirrors reducing spotted surface and increasing particles removal efficiency.
The cleaning process is related to the soil removal by erosion resulting from droplets impingement on the surface. It consists of four mechanism types: direct deformation, stress wave propagation, lateral outflow jetting and hydraulic penetration. The first two are responsible for crack initiation in the erosion process as reported by many researchers.

The air entrainment process promotes the water-jet spreading followed by a decay of pressure which becomes more as the standoff distance increases with a subsequent reduction in the jet cleaning ability. To keep the jet cleaning ability on the nozzle axis, a standoff distance range has been considered during the cleaning process with a water velocity rage of 80-200 m/s, typically compliant in such cleaning operations.

By ANSYS CFX module we have modelled a stationary water-jet system with a single nozzle setup that impinges the jet perpendicular to the flat surface. Several simulations have been carried out varying standoff distance, jet pressure and jet impingement angle in order to identify effective and efficient cleaning procedures to restore heliostats reflectance and CST plant efficiency.
Experiments with an array of three nozzles in line are considered in this study in order to evaluate the interaction of the two outermost nozzles with the middle one.

NOMENCLATURE

x	[m]	Distance from the nozzle exit
r	[m]	Distance of the considered point from the nozzle axis
R	[m]	Radius of the jet
D	[m]	Diameter of the nozzle
C	[-]	Spreading coefficient
r_0	[m]	Radius of the nozzle
R_{patm}	[m]	Radial distance from the jet axis
x_c	[m]	Critical standoff distance
P	[Pa]	Pressure generated during the impact
C_0	[m/s]	Sonic speed of liquid
V_0	[m/s]	Impact velocity
H	[m]	Standoff distance
Special characters		
ρ_0	[kg/m^3]	Liquid density
ϑ	[°]	Angle of impingement

KEYWORDS

Water-Jet system; O&M; Surface Cleaning; Water Spray Technology; Mirrors Cleaning; CFD; SEGS; CSP; Renewable Energy; Droplets Impact; CST

INTRODUCTION

The cleaning process, as part of the operation and maintenance (O&M), represents one of the most costly expenses of concentrated solar power plants (CSP). An accurate and detailed strategy on mirror cleaning is fundamental to enhance optical performance and ensuring the cost-effectiveness of CSP systems [1].

In the last three decades, a consistent amount of studies on cleaning aspects and techniques such as spray technology, abrasive water-jetting (AWJ), air-jet impingement on flat smooth and rough surfaces have been conducted in addition to related research in similar sectors such as droplet impact dynamics, soil erosion and soiling mitigation.

Manufacturing industry uses stationary water-jet for cutting and cleaning operations. The main difference is that the water-jet for cleaning purpose does not require the jet penetration into the solid, as the cutting water-jet does, since it involves an erosion process by which soils are removed from the surface [2].

The cutting process has been analyzed from an analytical and experimental point of view to evaluate the hydrodynamic forces and the optimal standoff distance [3, 4].

According to findings carried out mostly from 1978 to 2011, several scientists focused on jet impingement topic and connected cleaning aspects, carrying out experimental tests. The majority of that research, except most recent studies, lack a mathematical model. Therefore the understanding of the effect of parameters in the cleaning process was incomplete and limited by the outputs that were accessible to those early stage experiments. [2, 5, 6].

Experimental and numerical studies on water-jet cleaning process conducted by Guha et al., based on the semi-empirical model to capture the air entrainment process and to bypass the theoretical limitations, reveal the optimal standoff distances are in the range 5D - 26D. Upper and lower bounds represent the critical stand-off distances outside of which no cleaning ability was observed. Furthermore researchers inferred that soil located at a radial distance $R_{Patm} > 1.68D$ of the jet axis is definitely irremovable by the cleaning jets.

Leu et al., established a mathematical model of significant importance for cleaning operations, highlighting that cleaning occurs when the shear stress generated by water droplets impact is greater or equal to the endurance limit of the coating material. This study established that the maximum cleaning width is linearly proportional to the critical standoff distance, and optimal cleaning occurs at $0.576x_c$ [2].

Air and water spray technique are the most conventional methods available for cleaning purposes. Particle removal as spray-jet is strongly connected to shear stress generated on the target surface. Cleaning efficiency increases by maximizing the fluid velocity on the surface and decreases as the spray breaks into smaller droplets on the target surface[7].

Accordingly to Adler's research study, the soil removal process is strongly dependent upon material erosion by droplets impingement on surfaces. It consists of four mechanism types: direct deformation, stress wave propagation, lateral outflow jetting, and hydraulic penetration. The first two are responsible of cracks initiation in the erosion process as reported by many researchers[8].

Experimental and theoretical studies regarding single droplet impacting on several types of surface which can absorb more or less energy have been carried out by many researchers[9-15]. Preliminary studies, based on a single droplet impacting on rigid surface, showed a misshapen droplet compressed at its base or point of contact. These studies, based on the water hammer theory on one-dimensional approximation, explain the soil erosion is due to the pressure generated from planar shock wave at a constant speed C_0.

According to this theory the following relations holds:

$$P = \rho_0 C_0 V_0 \tag{1}$$

Further experiments provided a two-dimensional model for a better approximation of the maximum pressure before droplets spread on surface and rectified the previous hypothesis of single shock wave with a multiple wavelet structure[9, 11, 15].

Soil removal is correlated to the shear stress magnitude imposed on the target surface and it can be obtained using a variety of methods concentrating the shear stress.

Air-jet impingement is one of those effective methods, and probably the most common for cleaning purposes, as it imposes a consistent shear stress. Several studies have been conducted with this cleaning technique.

Zhang et al., conducted an experimental research based on the particles removal, glass sphere of 40-50 micron, by a single air jet using a converging nozzle with 3mm of diameter. The experimental study showed how the standoff distance, jet impinging, inlet pressure and time elapsed strongly affect the removal efficiency. It was found that a 30 degree impinging angle entails the greatest result in terms of particle removal in conjunction with impinging distances from 13D to 20D (39 to 60mm)[16, 17].

Vachon et al., conducted a study on dust mitigation as particulate strongly adheres to surfaces such as solar panel, clothing, equipment and mechanical devices by imposing a bound vortex surface impingement method[18].

In the water-jet cleaning context there is a lack of knowledge in enhancing shear forces to improve particles removal efficiency, hence the purpose of this paper is to provide a practical procedure for a more effective cleaning operation. It focuses on the variation of parameters such as inlet pressure, angle of impingement and standoff distances, and their combination, aiming to enhance the shear stress on a specific portion of the target surface for an efficient cleaning process.

WATER-JET STRUCTURE

Three regions characterize the jet structure:

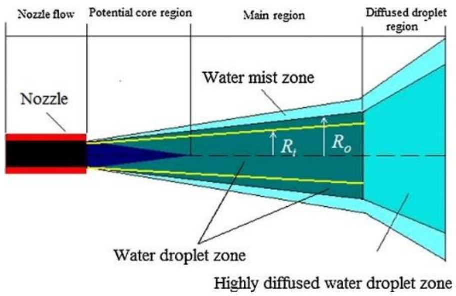

Figure 1 Water-jet characterization [5].

- *Potential core region*: this is the closest part to the nozzle exit (Figure 1), and it is characterized mostly by a wedge-shape area surrounded by a mixing layer where the process of air entrainment breaks up continuously water into droplets due to an intensive transfer of mass and momentum. The velocity inside the core region is equal to the velocity at the nozzle exit.
- *Main region*: the continuous interaction between air and water results in the breakup of the water jet stream into droplets which decrease their size progressively as the radial distance increases. The area close to the nozzle or jet axis is known as the water droplets zone whereas the mist zone is characterized by small droplets with negligible velocity useless for cleaning purposes.
- *Diffused droplet region*: In this area the jet is totally broken into small droplets with insufficient velocity for cleaning purposes.

It has been proven that bigger water droplets sizes are concentrated along the central line of the water jet becoming smaller moving along the radial distance of the jet stream. [6]

From the investigation of Yanaida and Ohashi followed by Zou et al., the radius of the jet R is related to the distance from the nozzle exit, x, as follow:

$$R = Cx \quad (2)$$

C represents the spreading coefficient and its value comes from experimentally observation. It is estimated to be about 0.03 in the main region and increases to 0.06 to the diffusion region [19, 20].

Many studies on surfaces cleaning by water-jet technology showed that the cleaning area width does not match with the jet width because the water-jet is more powerful in terms of pressure in the main water droplets region. As the standoff distance increases the surface tension generated by the impact of pressure decreases.

In the mist zone and in the diffused water droplet zone because of the low pressure the cleaning efficiency falls down drastically. The distribution of forces impact follows the Gaussian distribution so the strongest pressure is at the center of each jet cross section decreasing to zero moving to the edges as is shown in the figure 2 [21].

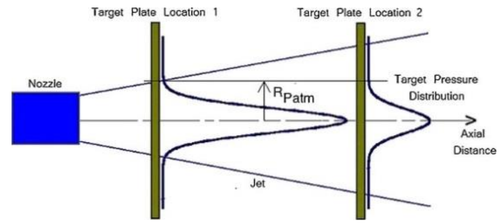

Figure 2 Pressure distribution on target plates with different standoff distance[21].

Accordingly with Guha's experimental findings, the optimal standoff distance is in the range ∼5D from the nozzle exit, and the jet loses its cleaning ability at ∼26D (critical stand-off distance). Keeping the target plate too close to the nozzle causes the jet to rebound from the cleaning surface and obstruct the nozzle flow, decreasing cleaning efficiency. On the other hand, if the surface is kept too far from the nozzle, the jet will transfer momentum to the surroundings, producing huge pressure loss and thus inefficient cleaning.

Guha et al., inferred that soil located at a radial distance $R_{Patm} > 1.68D$ of the jet axis is not removable by the cleaning jets [5].

Considering a wall impingement by multiple jets on the target surface, jets of adjacent flows may impact carrying the merged flow away from the wall into a "fountain" shape as shown in figure 3

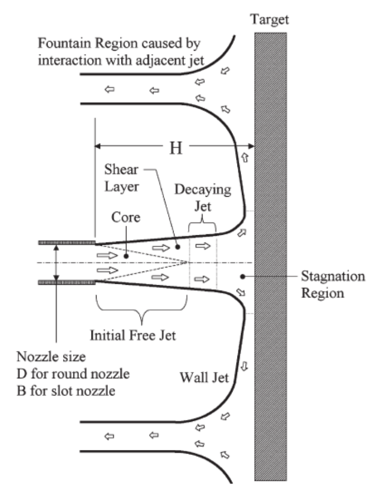

Figure 3 Fountain regions can occur as adjacent flow collision.

These fountains, in function of the H/D ratio, can occur nearby jet flows interacting with them and responsible of eddies development [22].

METHODOLOGY

Initial geometries, nozzles, flat target surface and volume of control were created in SolidWorks 2013, parametric three-dimensional modelling software which is effective and straight for modifying complex parametric geometries. Nozzles chosen for this study are full cone types, with a section of 30x20mm and 2mm of diameter. In the array setup, the distance between nozzles is fixed at 60mm to control adjacent flows interaction avoiding cleaning inability.

These geometries were imported into ANSYS Workbench v.15 and processed with CFX package.

A computational domain was created around each nozzles geometry and the target flat surface. The size of the domain (600 x 300 mm) was chosen to insure all surface impingement characteristics were captured. Regarding the mesh phase, tetrahedral elements were applied throughout the entire domain followed by a manual refinement on grid resolution with minimum size of 0.001 mm, maximum size of 5 mm and maximum facet size of 3mm. In function of several simulations carried out, tetrahedral elements vary from approximately 1,190,000 to 1,468,000 because of standoff distances changes. The mesh resolution created on the target surface is characterized by more than 4000 elements per meter, sufficient to provide a mesh independent result for the shear stress generated [18]. An example of the meshed domain can be seen in figure 4.

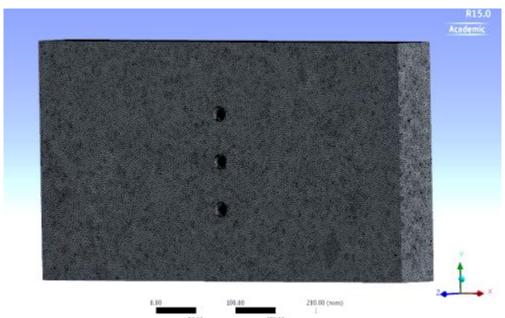

Figure 4 Mesh domain with three nozzles in line with a fixed distance of 60mm

COMPUTATIONAL MODEL

A computational fluid dynamics setup followed the meshing phase, in which all the boundaries were properly defined. A note of evidence is considered during the approach of angled impingement as the fluid flow is not normal to the boundaries, hence a transformation from Polar to Cartesian coordinates was applied as follows:

$$\begin{cases} x = 0 \\ y = -Hsin\vartheta \\ z = -Hcos\vartheta \end{cases} \tag{3}$$

Considering the turbulence model the SST model represents a good method for limited computational power required with adequate wall impingement prediction. It was chosen as a combination of the k-epsilon in the free stream and the k-omega models near the walls. It does not use wall functions and tends to be most accurate when solving the flow near the wall. [22]

The flow field at the initial time was set to zero, and the previous converged solutions were used at the initial condition for each successive study in order to decrease computational demand by reducing the iteration required to reach a converged solution.

Shear stress on the impacted flat surface was retrieved in each case study in function of different impinging angles and inlet pressures. This research analyzes the shear stress generated, after the jet impingement, at seven steps of pressure (5, 10, 15, 20, 30, 50, 70 [Pa]), three levels of standoff distance (5D, 15D, 25D) and two angles of impingement (ϑ= 90 and ϑ=75 degree).

RESULTS

SINGLE NOZZLE SETUP

In a single nozzle setup, results confirm high shear peaks as the inlet pressure is increased. In figure 5 the water-jet behavior at three different levels of standoff distances is shown. For low inlet pressures, there is not much difference in the shear forces peak. More significant differences occur after a pressure of 20 Pa, especially between 5D and 25D standoff.

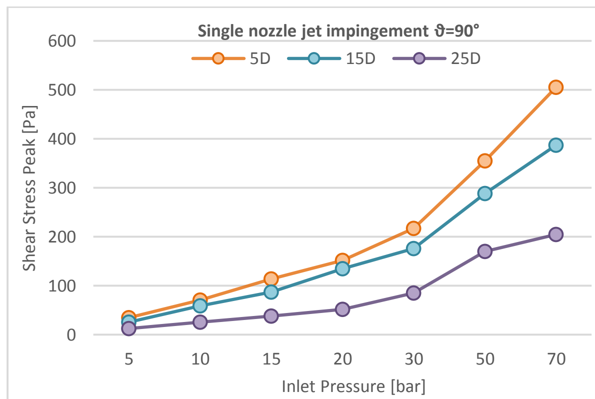

Figure 5 Water-jet impingement with ϑ= 90° and at three standoff distances for the single nozzle setup

The shear stress generated on the target surface increases as standoff distance decreases.

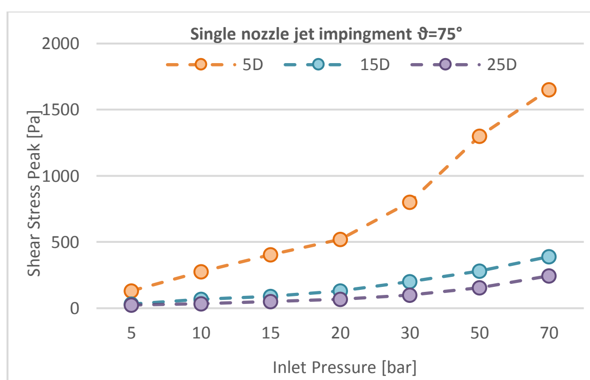

Figure 6 Water-jet impingement with ϑ= 75° and at three standoff distances for the single nozzle setup

Examining the results for an impingement angle ϑ=75° figure 6, the overall trend does not change.

The tilt effect of the jet impingement, highlights a concentration of shear stress on the lower part of the impingement.
The average shear forces enhancement per standoff distances by tilting the jet 15° from the normal impingement scenario, shows a remarkable improvement for 5D standoff distance and modest enhancements of 3% and 10% for 15D and 25, respectively as shown in figure 7.

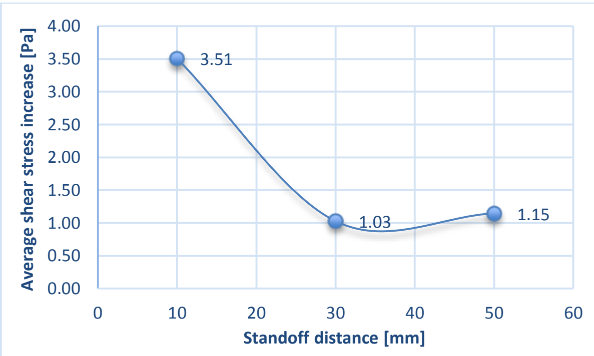

Figure 7 Average shear stress enhancement in a single nozzle setup

ARRAY SETUP WITH 3 NOZZLES

Further simulations have been carried out considering an array of 3 nozzles aligned.
In this configuration, of particular interest is to analyze the jet flow trend as it is affected by the adjacent jets.
Common water-jet cleaning systems available in the market have multiple nozzles aligned and mounted on a long boom. Except for the outermost nozzles, the inner ones are expected to have the same tendency of the nozzle positioned in the middle of our 3-nozzle configuration.

The water-jet impingement and interaction between nozzles changes the overall scenario in comparison with the single setup.

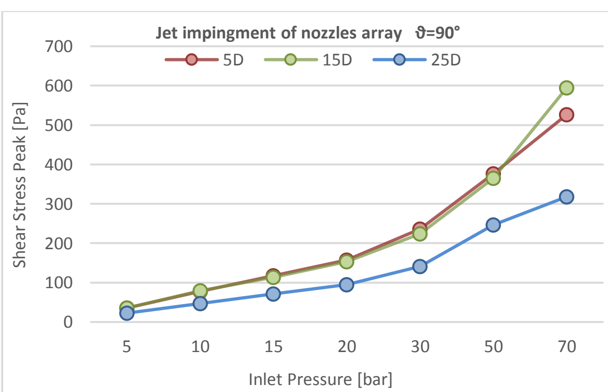

Figure 8 Water-jet impingement of nozzles array setup at three standoff distances and ϑ= 90°

Examining results for the shear stress generated at 5D is very similar to 15D because of the ratio H/D < 6 ,figure 8.
In this scenario the core of the jet is still developing hence the water velocity profile is not fully developed when reaching the target plate [23].

Significant turbulence occurs for 15D standoff distance at the inlet pressure 50 Pa, as shown in figure 9.

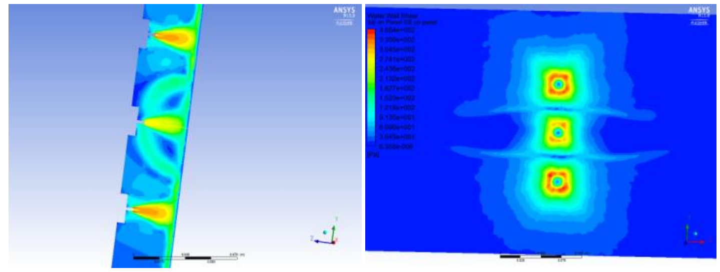

Figure 9 Turbulence at 15D with inlet pressure 50 Pa

At 25D the turbulence developed by the nozzles interaction is quite evident examining the water velocity contour placed on the plane section of the control volume, figure 10. Fountain regions begin, as interaction of adjacent jets, deflecting to the central nozzle with a subsequent decrease of the jet velocity and cleaning efficiency.

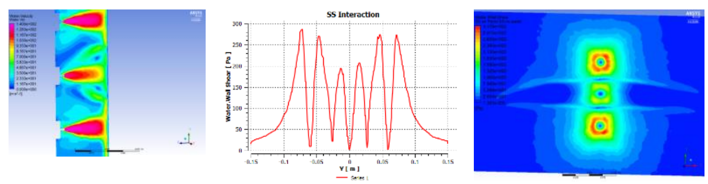

Figure 10 Significant turbulence that occurs at 25D with 70 Pa inlet pressure.

Results conducted with the impingement angle ϑ=75°, obtained tilting nozzles axis 15° from the perpendicular impingement, show an enhanced shear forces peak at 5D standoff distance, and a modest increase for 15D and 25D scenarios, figure 11.

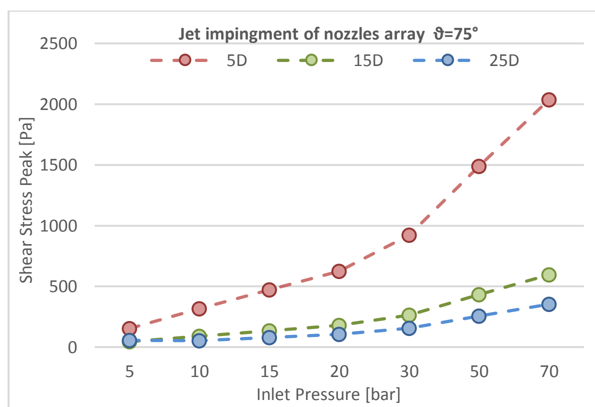

Figure 11 Water-jet impingement of nozzles array setup at three standoff distances and ϑ= 75°

As observed in the single nozzle setup scenario, an intensive shear stress enhancement occurs for the 5D standoff distance whereas 15D and 25D standoff register a smaller improvement of 11% and 12% respectively as shown in figure 12.

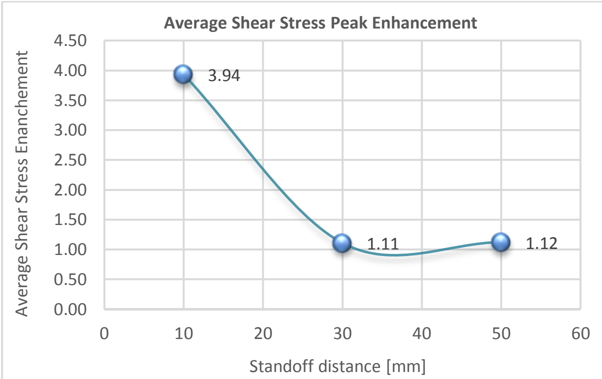

Figure 12 Average shear stress enhancement for the 3 nozzles setup

CONCLUSION

In this paper a detailed study for water-jet impingement on vertical surface has been performed with a single and multiple nozzles configuration. Three different standoff distances in conjunction with the variation of inlet pressure and angle of impingement have been considered in the CFD simulations by ANSYS v15 software.

Findings confirm a significant increase of shear stress as the standoff distance decreases. Varying the angle of impingement from $\vartheta = 90°$ to $\vartheta = 75°$ for both configurations, an enhancement of shear forces occurs for all standoff distances but is more remarkable at 5D. Moreover, a general decrease of interaction between adjacent flows is observed with the discontinuance of fountain regions. This translates to a low presence of turbulence and an enhanced cleaning efficiency for the central nozzle of the array.

Further studies will continue this research by carrying out simulations with different impinging angles and nozzles setup in conjunction with experimental tests.

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