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# Numerical Analysis of The Effect of Nozzle Geometry on Flow Parameters in Abrasive Water Jet Machines

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## ABSTRACT

The nozzle of the AWJ machine is a critical component which has direct influence on the jet force developed. In the present scenario, commercially available nozzles have conical section followed by focus section. The critical section is where the cross section of the nozzle changes from conical to straight and suffers severe wall shears stress leading to flow loss. In considering this, computational analysis has been carried on the jet flow through AWJ nozzle with different nozzle geometries. The geometric variation of nozzle profiles show that, reduction in radius of curvature (radius 20 mm) of nozzle geometry produced higher jet velocity and force, as well as lower pressure drop compared to other geometric dimensions.

*Keywords*: AWJ nozzle, jet force, SOD, CFD analysis, garnet abrasive

## INTRODUCTION

Technological advancements have made Abrasive Water Jet (AWJ) as a one of the promising field of non-conventional machining. Presently, AWJ machines are developed to operate with pressures up-to 1000 MPa for cutting and drilling applications on various materials. The critical component of the AWJ machine is the nozzle which has direct influence on the jet force developed. In the present scenario, commercially available nozzles have conical section followed by focus section. The critical section, where cross section of the nozzle changes from conical to straight suffers severe wall shears stress which leads to flow loss and jet energy (Deepak et al., 2012). There are cited literatures on nozzle flow based on experimental and numerical methods. Jiang

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et al. (2013) studied the influence of grid size on the accuracy of the numerical simulations. The effect of inlet pressure and particle size on the jet flow field was studied by Deepak et al. (2011). Due to the geometrical structure, the velocity of the jet was found to increase up-to critical section of the nozzle and thereafter it decreased slightly in focus section due to Wall Shear Stress (WSS). Optimum focus length of nozzle was determined by Hu et al. (2008).

Meanwhile, Taggart et al. (2002) investigated the effects of abrasive flow rate, length, cone angle and diameter of nozzle, as well as inlet water pressure on nozzle wear by experimental method. The nozzle length exhibited a direct influence on the exit jet diameter, which delays the development of wear profile from reaching the exit. Flow pattern within the nozzle was unaffected by its length. Increase in the inlet angle exhibited non-linear increase in bore of the nozzle. The optimum diameter ratio of the nozzle was found to be between 0.3 and 0.4. Increase in the abrasive flow rate resulted in increased nozzle wear rate without changing the wear pattern, but increase in water pressure exhibited maximum wear rate. Anand and Katz (2003) developed porous nozzle which reduced nozzle wear by providing lubrication. The oil film was also found to improve the coherence of the jet. Erosion rate of the boron carbide nozzle was found to increase with increase in abrasive hardness (Deng, 2005). The nozzle entrance area suffered from severe abrasive impact under large impact angles, at the nozzle centre wall section, most of the particles travelled parallel to the nozzle wall, and showed minimum tensile stress. The wear mode in this area was found to be changed from impact to sliding erosion and the wear mechanisms appeared to be the lateral cracking owing to a surface fatigue fracture.

Shimizu et al. (2008) studied the effect of abrasive particle size on jet structure that was formed after exiting the nozzle. For higher abrasive particle sizes, the jet diameter at the exit of the nozzle was found to increase with the increase in distance from the nozzle tip. The jet became unstable at a distance of about $x = 25 \times d_F$ and the jet broke up at a distance of about $x = 80 \times d_F$. In case of finer abrasive particle (mesh size: 220), stable compact jet was formed up to distance of about $x = 80 \times d_F$. This indicated that abrasive particles of larger size contributed to flow turbulence and promote the jet breakup at comparatively shorter distances. Vu and Nguyen (2009) developed model to predict the nozzle life at various operating conditions. Numerical investigation was made by Mabrouki et al. (2000) to study the effect of abrasive water jet impact on aluminium sheets.

Kasmol et al. (2001) developed a model using FEA to predict the depth of jet penetration onto work-piece. Simulations show that pure water jet has less interaction on target material, whereas with AWJ, a strong interaction with target material in terms of localised deformation was found. The developed model was validated with experimental results which were in good agreement. Yang et al. (2009) investigated the effect of SOD and fluid viscosity on jet performance. The higher the viscosity of fluid, the more coherent is the velocity distributions at the impacting region. A velocity distribution along the length of traverse till the target material was found to be different at different positions. Waviness in velocity distribution was seen on target material for SOD greater than 3 mm. Since the nozzle geometry also has an influence on the flow properties of the jet, the present work aims at jet force, pressure drop, WSS developed in nozzle having different profiles.

## THEORITICAL FORMULATION

### Numerical Model

Computational domain consists of converging of nozzle having length 4 mm along the axis of the nozzle. The length of the converging section of the nozzle is 10mm with focus section of length 5mm. The profile of the nozzle is varied with radius 20 mm, 40 mm, 60mm and their flow characteristics are compared with the nozzle having straight conical section.

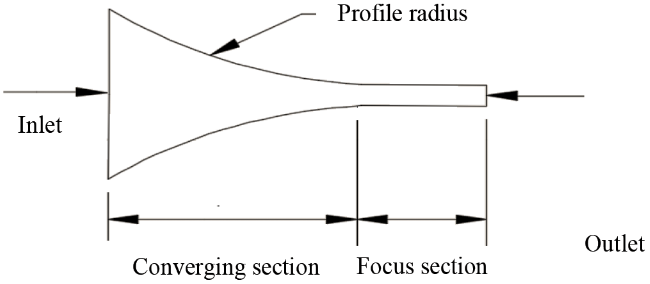

*Figure 1*. Profile of the AWJ nozzle for flow analysis

The inlet and exit diameters are maintained constant for all nozzles at 8mm and 1mm respectively. The mixture of abrasive and water is let into the nozzle at the inlet and is carried down through the converging cone to the focus tube and exits as coherent jet at the nozzle exit, in which the focus tube is used for stabilising the flow. Figure 1 shows the numerical region for flow analysis. The governing equations for mass and momentum conservation are solved for the steady incompressible flow. The coupling between velocity and pressure has been attempted through the phase coupled SIMPLE algorithm. The standard k–ε turbulence model is used to predict the flow physics with standard wall functions. The governing partial differential equations for mass and momentum conservations are detailed below.

### Continuity Equation

$$\frac{1}{\rho_{pq}}\left[\frac{\partial}{\partial t}(\alpha_q \rho_q) + \nabla\bullet(\alpha_q \rho_q v_q)\right] = \sum_{p=1}^{N}(m_{pq} - m_{qp}) \qquad [1]$$

### Fluid-Solid Momentum Equation

The conservation of momentum equation for the solid phase is as follows.

$$\frac{\partial}{\partial t}(\alpha_s \rho_s v_s) + \nabla\bullet(\alpha_s \rho_s v^2{}_s) = -\alpha_s \nabla p - \nabla p_s + \nabla\bullet \tau_s + \alpha_s \rho_s g +$$

$$\sum_{l=1}^{N}\left[k_{ls}(v_l - v_s) + (m_{ls} v_{ls} - m_{sl} v_{sl})\right] + (F_s + F_{lift,s} + F_{vm,s}) \qquad [2]$$

The conservation of momentum equation for the fluid phase is as follows.

$$\frac{\partial}{\partial t}(\alpha_q \rho_q v_q) + \nabla\bullet(\alpha_q \rho_q v_q^2) = -\alpha_q \nabla p + \nabla\bullet \tau_q + \alpha_q \rho_s g$$

$$+\sum_{p=1}^{N}\left[k_{pq}(v_p - v_q) + (m_{pq} v_{pq} - m_{qp} v_{qp})\right] + (F_q + F_{lift,q} + F_{vm,q}) \qquad [3]$$

## Assumptions of the Numerical Analysis

Following assumptions are made for the formulation of numerical solution.

- The primary liquid phase is continuous and incompressible.
- Two-phase flow assumed is steady and characterized by turbulent flow.
- The Coanda effect is not considered on the flow.
- Flow is taken to be two-phase flow in which the primary liquid phase mixes homogeneously with the particles of equal diameter, constituting the solid phase.

## Numerical Scheme

Computational domain is discretised by quad cells. Conservation equations are solved for each control volume to obtain the velocity and pressure fields. Convergence is affected when all the dependent variable residuals fall below 0.00001 at all grid points. Wall region in the flow domain is closely meshed using the boundary layer mesh concepts for extracting high velocity gradients near the boundary walls as shown in Figure 2. According to the structure of nozzle and jet characteristics, computational domain is built as axis-symmetric model.

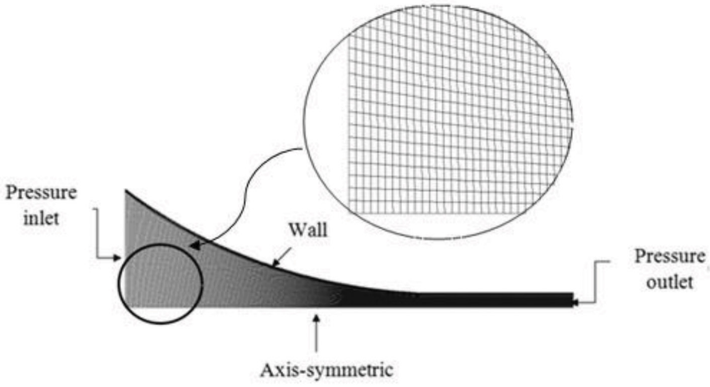

*Figure 2*. Computational domain with boundary conditions

### Grid Independence Test and Validation of the Results

Grid test is performed to check the quality of mesh for solution convergence. Figure 3 shows the velocity distribution along the length of the nozzle for grids of different sizes. It is clear from the graph that there is almost negligible variation in the velocity for the grids of different sizes. Considering the accuracy of the results and computational time, the geometry with appropriate number of grids are chosen for the study. Figure 3 also shows the velocity distribution along the nozzle axis, as obtained by the analytical formulations. It shows that results obtained from numerical simulations are in good agreement with the theoretical calculations.

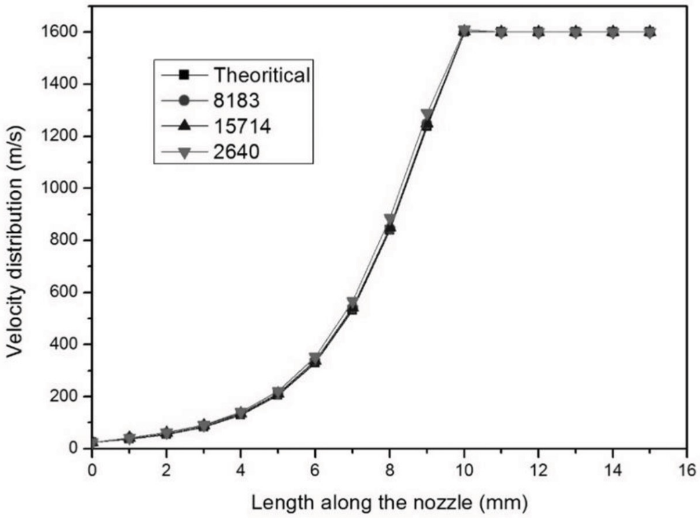

*Figure 3*. Velocity distribution for different mesh sizes

## RESULTS AND DISCUSSION

### Effect of nozzle profile on flow velocity

The profile of the nozzle is varied with radius of 20 mm, 40 mm and 60 mm as shown in Figure 1. Numerical simulations were carried out for the flow domain consisting of two phase mixture of water and garnet abrasive of diameter 160 µm. The inlet pressure is varied from 100 to 400 MPa and the corresponding velocities are shown in Figures 4(a) and 4(b) respectively.

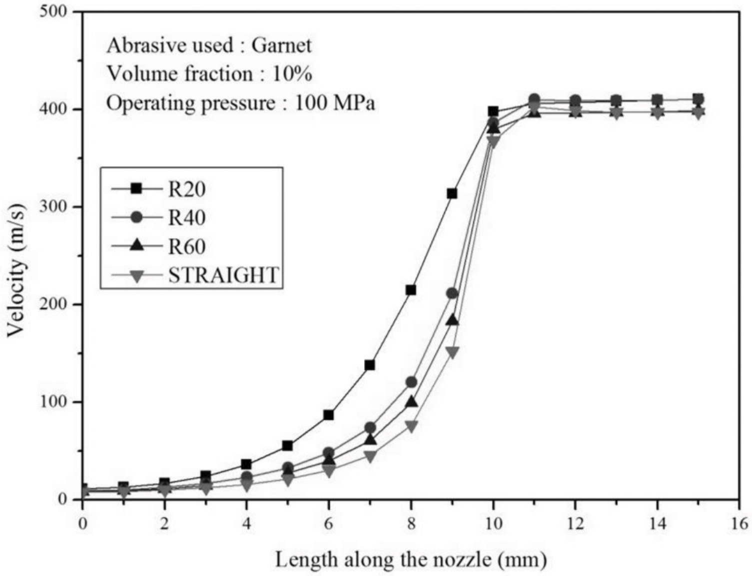

*Figure 4(a)*. Velocity distribution for nozzle profiles at inlet pressure 100 MPa

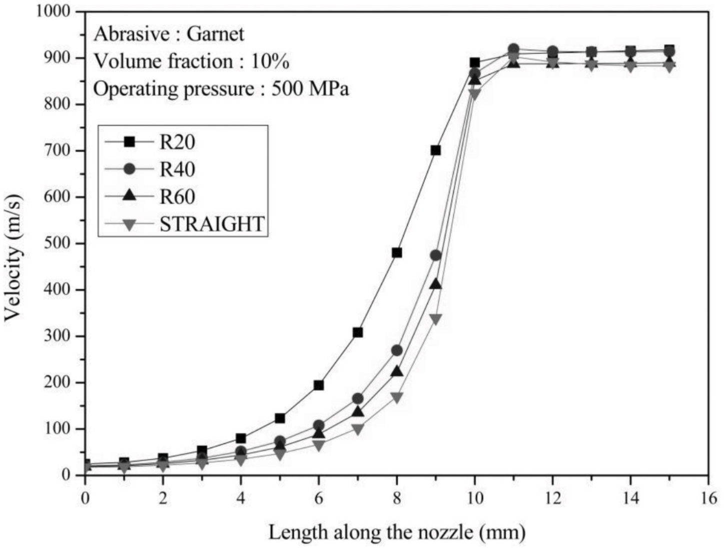

*Figure 4(b)*. Velocity distribution for nozzle profiles at inlet pressure 400 MPa

It was observed that the jet velocity increased along the axis of the nozzle and it reached peak exit velocities ranging from 400 m/s to 900 m/s for different inlet pressures. The jet velocity is found to rapidly increase for a axial distance of 10 mm, i.e. up to the region where cross-section changes to straight circular duct of length 5 mm at the end of the nozzle. The variation in the jet velocity remains almost constant in the focus section. From the geometrical variation of the nozzle profile, it was observed that there is an improvement in the jet velocity produced by the nozzle with curved inlet section compared to conical section. Further it is seen from Figure 4(a) and Figure 4(b) that the jet velocity increases with the reduction in radius of curvature from straight profile. The nozzle with profile radius 20 mm is found to produce maximum jet velocity compared to other geometries having 40 mm and 60 mm profile radius. Variation of the profile below 20 mm radious did not show any appreciable variations in the jet flow. The higher the radious of curvature, the higher the velocity gradiants are, leading to the corresponding flow loss particularly at the critical section. The nozzle with 20 mm profile radious produced smooth tranision in the jet flow which is almost parallel to wall surface of the nozzle, thus producing peak jet velocity.

## Effects of nozzle profile on jet force

The machinability of the material depends on cutting or jet force developed by the nozzle. Hence, in this study the cutting force developed by nozzles with different profiles were analysed at different operating pressures ranging from 50 MPa to 500 MPa. Figure 5 shows the cutting force developed by various nozzles corresponding to different inlet pressures. The cutting force is found to be increased linearly with the increase in inlet pressure. This is due to the increase in kinetic energy which increases with operating pressure (Deepak et al., 2011). Further, it is seen that, the cutting force is increasing with the decrease in the profile radius of the nozzle for the same operating conditions. The jet force developed in the nozzle depends on exit velocity. As explained earlier, nozzle with profile radius 20 mm produce higher jet velocity, the cutting force developed is also higher.

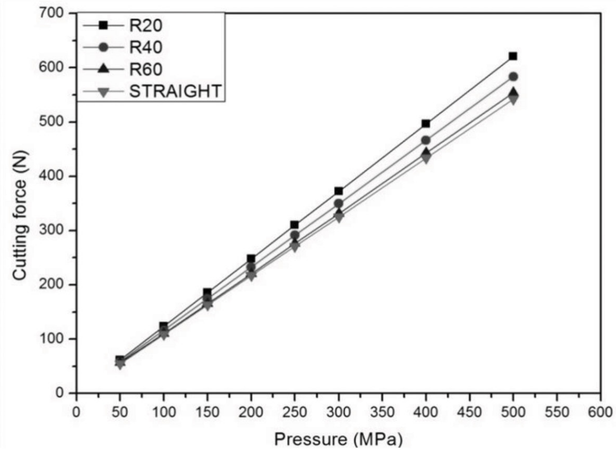

*Figure 5*. Cutting force distribution for various nozzle profiles

## Effects of nozzle profile on pressure drop

The total pressure change represents the potential energy loss in the nozzle. Figure 6 shows the pressure drops between jet entry and exit section of the nozzle for different geometric models at inlet pressure ranging between 50 to 500 MPa. It is observed that the profile of the nozzle greatly affects the jet flow. The pressure drop is found to increase with the increase in operating pressure for all geometries of the nozzle considered in the study. This is due to a higher wall shear stress at a higher operating pressures. Further, nozzle with profile radius 20 mm exhibits lower pressure drop compared to other models due to smooth transition of flow in the nozzle which resulted in generating higher jet force. Nozzles which have straight converging section and profile with increased radius leads to jet dispersion and hence resulting in a higher pressure drop.

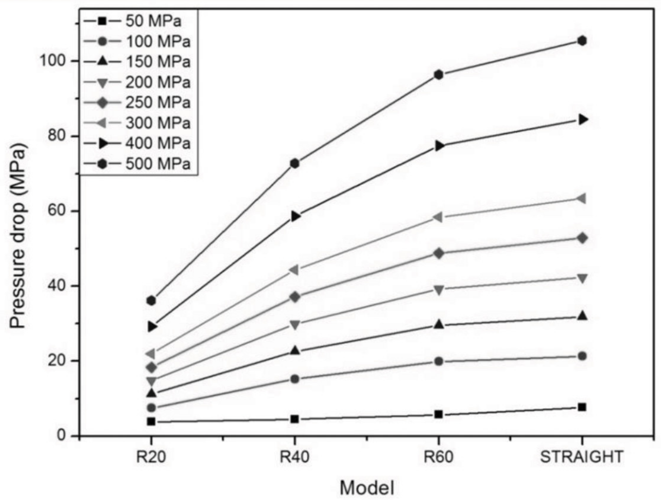

*Figure 6*. Pressure drop between jet entry and exit section

## CONCLUSIONS

A computational analysis has been carried on the jet flow through AWJ nozzle with different nozzle geometries. Based on the simulated results, the following conclusions are drawn. The geometric variation of nozzle profiles shows that, reduction in radius of curvature (radius 20 mm) of nozzle geometry produced higher jet velocity and cutting force as well as lower pressure drop compared with other geometric dimensions. The study also shows that irrespective of the nozzle geometry the jet velocity and force increased with increase in inlet pressure and it remains almost constant in the focus section of the nozzle. Hence, it is recommended to manufacture AWJ nozzle with the profiles having curvature against the current practice of having straight section.

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