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2016 IOP Conf. Ser.: Mater. Sci. Eng. 114 012016

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CFD Based Erosion Modelling of Abrasive Waterjet Nozzle using Discrete Phase Method

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Abstract. In Abrasive Waterjet (AWJ) machining, the nozzle is the most critical component that influences the performance, precision and economy. Exposure to a high speed jet and abrasives makes it susceptible to wear erosion which requires for frequent replacement. The present work attempts to simulate the erosion of the nozzle wall using computational fluid dynamics. The erosion rate of the nozzle was simulated under different operating conditions. The simulation was carried out in several steps which is flow modelling, particle tracking and erosion rate calculation. Discrete Phase Method (DPM) and K- ϵ turbulence model was used for the simulation. Result shows that different operating conditions affect the erosion rate as well as the flow interaction of water, air and abrasives. The simulation results correlates well with past work.

1. Introduction

Abrasive Water Jet (AWJ) Machining is a non-conventional machining process that is used in various industries in wide variety of applications. In the manufacturing industries, AWJ is commonly used as a tool for cutting, drilling, milling, cleaning, peening, forming, coating removal and surface roughening of materials surface [1, 2]. This is made possible by having abrasive grains entrained in a highly pressurized waterjet impacting the surface of the work piece and causes the material to erode [3]. The operating principles of AWJ process is formed by compressing the water inlet with high pressure then released from an orifice to be entrained with the abrasives in a mixing chamber [4]. The momentum is then focused in the nozzle resulting a slurry of thin stream of water jet containing abrasive particles, which accelerates with speed, high enough to cut through virtually any materials from hardened steel to soft foam materials [5].

One of the most associated problems with AWJ is the erosion in the wall of the nozzle. The nozzle needs to be replaced since the water travels at high velocity and contains abrasive particles which may deteriorate nozzle wall. Wear of nozzle bore decreases the mixing efficiency and reduces the coherence of the abrasive waterjet. Increased nozzle's outlet diameter will reduce transverse particle velocity and increased the kerf width. A commercial nozzle fabricated using rapid omni directional compaction (ROC) has life of approximately 50 – 100 hours [6, 7]. Kovacevic [8] has stated that under selected conditions, the optimal nozzle diameter is 2.2 mm which is 83% from the original diameter of 1.2 mm. Further increase will cause a significant decrease in the depth of AWJ penetration and deteriorates the surface quality of the machined sample.

Many researchers have studied multiphase flow sand erosion in horizontal pipe [9], pipe bends [10, 11] and in complex geometries [12]. On the other hand, studies using Computational Fluid Dynamics (CFD) in investigating erosion in AWJ nozzle are very limited. Mostofa et al. [13] used the ANSYS CFX software to simulate multiphase flow of water, air and abrasives in the mixing tube to monitor erosion rate at the mixing tube wall and predict the influence of abrasive particle size with different parameters of tube lengths. The erosion model is based on Finnie's erosion model of ductile



material. The result showed that abrasive shape and jet velocity have effect on erosion rate. The erosion rate has similar linear results as obtained by Nanduri et al. [7].

Deepak, Anjaiah, Karanth and Sharma [14] had also used ANSYS software to examine the effect of inlet pressure on skin friction coefficient and jet exit kinetic energy. According to the results, the effect of increasing the inlet pressure causes significant increase to the skin coefficient friction and increased in the jet kinetic energy correspondingly. Further analysis then suggested that by increasing the volume fraction of abrasives causes a significant decrease on both skin coefficient friction and jet kinetic energy.

In the present study, a CFD simulation was conducted using the ANSYS Fluent 15.0 to investigate the effect of erosion rate on the wall of AWJ nozzle with varying parameters of abrasive shape factor, and abrasive mass flow. The two phase discrete phase method (DPM) will be used for solving multiphase flow of water, air and abrasives particle.

2. Assumptions and theoretical formulation

The flow is assumed to be multiphase and the fluid is treated as continuum and incompressible. The particle's abrasive velocity is assumed to be the same as those of flowing fluid. The Lagrangian-Eulerian model is used to solve the coupling of the fluid flow and abrasives, also called discrete particle modeling, which solves the equations of motion individually for each particle, whereby in the case of continuous phase, it is modeled by using an Eulerian framework and the trajectories of the particles are simulated within a Lagrangian framework. In a two way coupling, each particle exchanges mass, momentum and energy with the fluid phase valid for the current work [14-18]. The theoretical waterjet velocity was used by Mostofa et al. [13] to validate their simulation model. Similarly the same theory is used to validate the simulation model for the present work. The equation for the water jet velocity at the orifice can be obtained by using the following theoretical formulation.

Theoretical waterjet velocity, V_{th} :

$$V_{th} = \sqrt{\frac{2p}{\rho}} \quad (1)$$

Compressibility of water:

$$\frac{\rho}{\rho_0} = \left(1 + \frac{P}{L}\right)^n \quad (2)$$

Where p is the operating pressure, ρ is water density (kg/m³), $L = 345$ Mpa and $n = 0.162$ at 25^o C. Note that value of L depends on the pumping pressure of the AWJ machine for the pump plunger to pumped before any water begins to exit the check valve.

The resulting equation for the waterjet velocity:

$$V_j = \sqrt{\sqrt{\frac{2L}{(1-n)\rho_0} \left[\left(1 + \frac{P}{L}\right)^{1-n} - 1 \right]}} \quad (3)$$

Compressibility factor:

$$\varphi = \frac{V_j}{V_{th}} = \sqrt{\frac{L}{P(1-n)} \left[\left(1 + \frac{P}{L}\right)^{1-n} - 1 \right]} \quad (4)$$

The waterjet velocity can then be expressed in the following equation:

$$V_j = C_d \varphi V_{th} \quad (5)$$

Where discharge coefficients, $C_d = 0.85$. The value is based on the function of the jet size from past research [13].

Using the particle erosion and accretion method to enables erosion rates to be monitored at wall boundaries. The erosion rate equation is defined as below:

$$R_{erosion} = \sum_{p=1}^n \frac{\dot{m}_p C(d_p) f(a) v^{b(v)}}{A_{face}} \quad (6)$$

Where $C(d_p)$ is a function of particle diameter, a is the impact angle of the particle path with the wall face, $f(a)$ is a function of impact angle, v is the relative particle velocity, $b(v)$ is a function of relative particle velocity, and A_{face} is the area of the cell face at the wall. Default values are $C = 1.8 \times 10^9$, $f = 1$, and $b = 0$. The erosion rate density is presented in the unit of kg/s/m², noted that this value just represent the qualitative value and not the physical value which reflect the actual materials being used.

K- ϵ turbulence model is used to simulate turbulence for mixed flow of water, air and abrasive of an AWJ process. The turbulence quantity is specified using the Percentage Intensity, I , which is defined as the root-mean-square of the velocity fluctuations, u' , to the mean velocity $u_{average}$. The value of the turbulence intensity specified at water pressure inlet boundary conditions are defined as below:

$$I = \frac{u'}{u_{average}} = 0.16(Re_{Dh})^{-1/8} \quad (7)$$

The Reynold's number, Re , for given size of the hydraulic diameter, D_h , of the AWJ waterjet circular tube were obtained using the following equation:

$$Re_{Dh} = \frac{\rho u D_h}{\mu} \quad (8)$$

Where, Re is Reynolds number (non-dimensional), u is velocity based on the actual cross section area of the duct or pipe (m/s), μ is the dynamic viscosity (Ns/m²) and L is the characteristic length (m) and ν is the kinematic viscosity (m²/s).

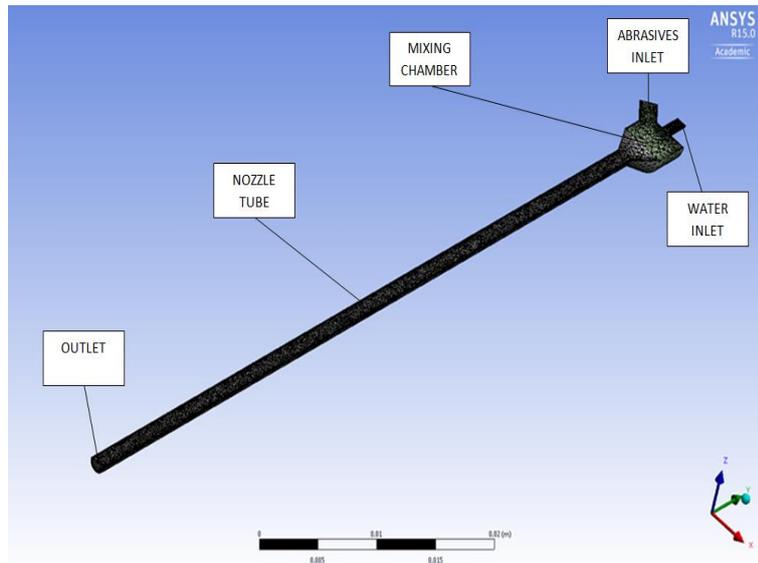
3. Geometry and parameters

The numerical model is based on the 3-D model of commercial AWJ cutting head from previous research [13]. The geometrical and parameters are defined as shown in Figure 1 (a). High pressured waterjet and abrasive are released from their corresponding inlet and mixed into the mixing chamber where entrainment occurred and focused to the nozzle tube and eventually released. The model was then meshed by using the standard meshing in FLUENT 15.0. The wall of the nozzle was meshed using inflation by selecting the surface selection option to simulate wall interaction with the fluid flow.

The numerical model is based on the 3-D model of commercial AWJ cutting head from the past research[13]. The geometrical boundary and parameters are defined as shown in Figure 1 where (b). Highly pressurized waterjet and abrasive are released from their corresponding inlets and mixed inside the mixing chamber where entrainment occurs. Then, the mixed waterjet and abrasive flow will be transported along the nozzle tube and eventually released at the outlet. The model is meshed using the standard meshing in FLUENT 15.0. The wall of the nozzle is meshed using inflation by selecting the surface selection option to simulate wall interaction with the fluid flow.

Table 1 shows the parameters for boundary conditions. The shape factor is a parameter for the abrasive particles irregularity. A shape factor of 1.0 signifies a particle with a circular shape while decrease of value signifies increase of irregularity. The particle mesh size chosen was 140 or approximately 0.1 mm in diameter and is assumed to be uniform for simplification of the solution.

(a)



(b)

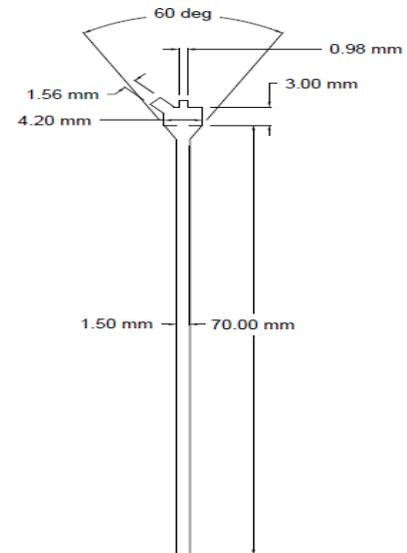


Figure 1. Cutting head (a) Geometry Designations (b) Geometry values

Table 1. Boundary condition and parameter values

Boundary Conditions	Parameters
Abrasive Mass Flow Rate	8 (typical), 20, and 30 g/s
Abrasive Density	7854 kg/m ³
Abrasive Shape Factor	1, 0.9 and 0.7
Water Pressure	470 MPa
Water Density	1000 kg/m ³
Abrasive Inlet Mesh Size	140 (100.1 microns)

4. Results and discussions

In order to validate the model, equation (1), (3) and (4) were solved for water pressure of 470 MPa and the following values were obtained where $V_{th} = 970$ m/s, $V_j = 934$ m/s and $\varphi = 0.96$. The values then inserted into equation (5) and $V_j = 791$ m/s. Based on the simulation conducted, similar results were obtained for the velocity profile along the x axis and maximum velocity at orifice as shown in Figure 2. The chart was separated into two domains; the first domain is the waterjet velocity in the mixing chamber which is 3 mm in length. Then, the variation continues onto the nozzle tube domain which has the length of 70 mm. In the beginning of the flow, the value starts with velocity of water of around 795 m/s. Therefore, the value of the simulated velocity agrees with the theoretical waterjet velocity. A drop of waterjet velocity is observed as the flow begins to enter the mixing chamber. The increased diameter of the chamber's geometry causes the velocity to decrease. Here, abrasive particles were also beginning to start entraining with the waterjet flow. As flow progresses, the waterjet velocity is beginning to increase. This is due to the decreased diameter in the nozzle tube which helps to increase the waterjet velocity. The waterjet velocity then remains constant throughout the nozzle tube and exits the nozzle with velocity of 380 m/s. The same velocity distribution were also compared with other models where similar results were obtained [13, 14].

Figure 3 shows the mixing of air and water in the mixing chamber. In the present simulation, the turbulence of water, air and abrasive particle were done by using the K- ϵ turbulence model. The turbulence intensity for the simulated water pressure was obtained using equation (7). The increase of turbulence intensity will affect the characteristic of turbulence between phases. As the waterjet released from the orifice, the air and abrasives were drawn up to the inlet of the orifice before getting entrained with the flow of waterjet. The similar water and air flow characteristic were described by Powell [19]. The same characteristic was also observed in the simulation attempted by Mostofa et al. [13]. It is described that the waterjet created a vortex that pulled the abrasive particle to be transported into the nozzle tube.

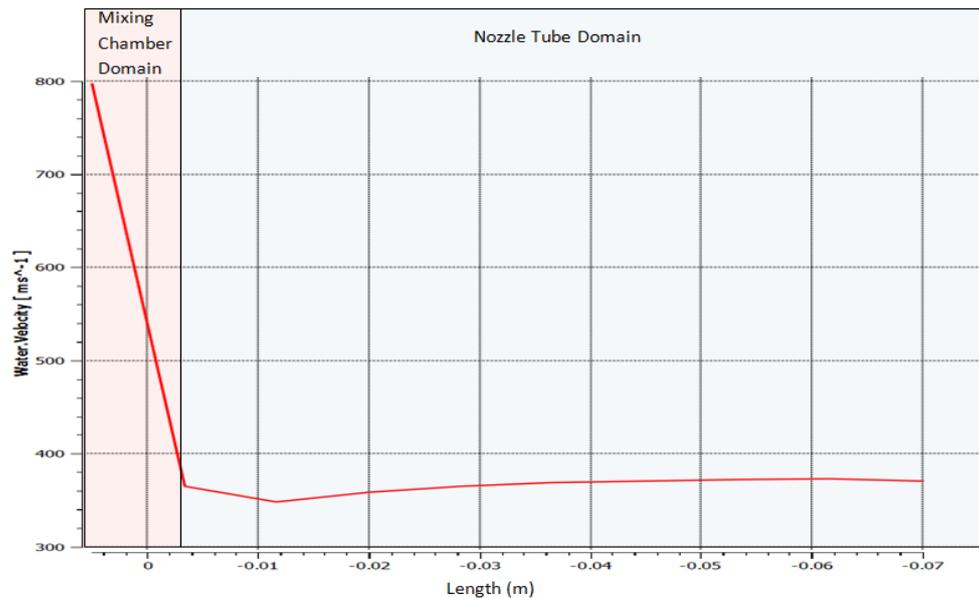


Figure 2. Waterjet velocity variations along the cutting head.

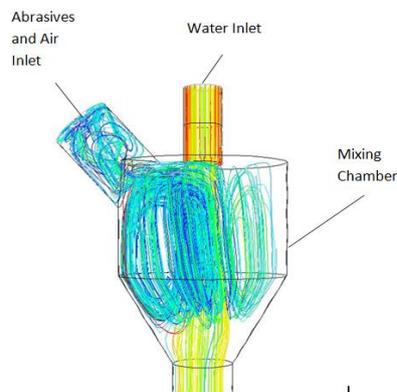


Figure 3. Path line of water and air in mixing chamber.

Figure 4 shows the contour of erosion rate along the nozzle tube. High erosion concentration was observed at the focus inlet tube of the nozzle. Pattern of erosion concentrations then continued along the nozzle wall which is consistent with findings by Nanduri et al. [20]. Particle tracking of the abrasives was shown in Figure 6. It is observed that the abrasives particles were pulled into the jet flow in the mixing chamber. Particle abrasives are transported into the nozzle tube by suction effect of the jet flow in the mixing tube. As shown in Figure 5 (a), air that is entrained during this process, served as the abrasive carrier [21]. The suction process is mainly due to the pressure gradient. A closer view in Figure 5 (b) supported the theory of suction created by the waterjet. The abrasive particle are shown to collide with the nozzle wall and reflected back. The DPM particle interaction allows the particle to transfer necessary information for erosion rate calculation.

An attempt has been made to study the effect of the shape factor of the particle to the erosion rate of the material. By applying shape factor, the shape or roundness of the particle can be modified. In Figure 6, it shows the effect of shape factor with (a) nozzle wear and (b) abrasive velocity. When the shape factor is reduced to 0.9, the erosion rate went slightly higher along with the velocity. This is similar to previous work where the shape factor has been modified with the different mesh size. This indicates that using irregular shape will produce better surface for cutting process [13].

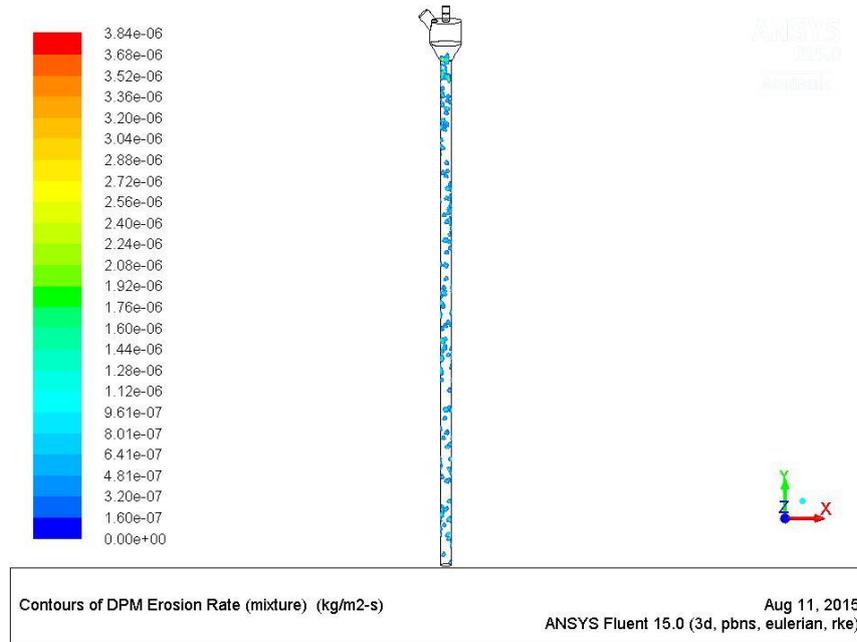


Figure 4. Erosion concentration along the nozzle tube wall.

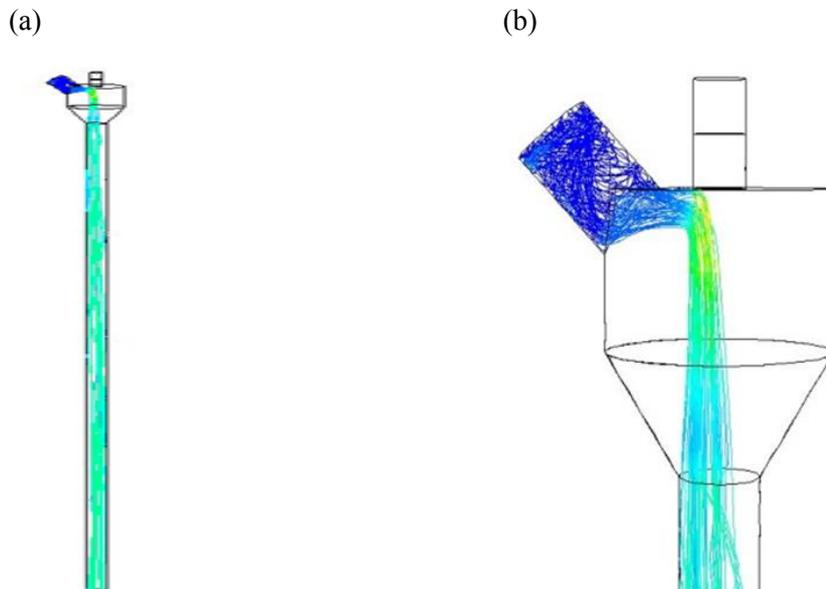


Figure 5. Waterjet abrasives particle tracking. (a) Along cutting head and (b) mixing chamber.

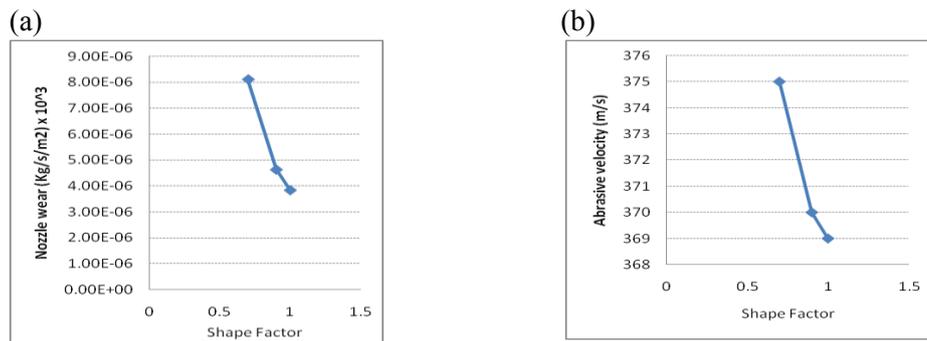


Figure 6. Effects of particle shape factor (a) Nozzle wear and (b) abrasive velocity.

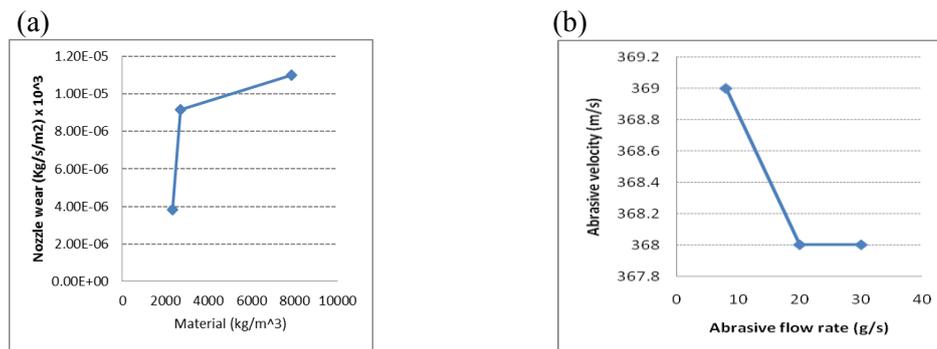


Figure 7. Effects of abrasive flow rate (a) Nozzle wear and (b) abrasive velocity.

The same simulation was conducted using different abrasive flow rate as shown in Figure 7. The result shows that there is an increasing trend of abrasive flow rate which also increases the nozzle wear rate on the nozzle wall. There is also slight decrease of the abrasive jet velocity. Previous research shows that by increasing the abrasive flow rates will increase the wear rate without changing the wear pattern [20]. However it is reported that the abrasive velocity decreased as the amount of abrasives flow rate increased. From the simulation, we can assume that the change of velocity is only minimal.

5. Conclusion

The ultimate objective of the simulation is to simulate erosion of the AWJ nozzle using the DPM method which is available in ANSYS FLUENT 15.0. The simulation results show that the variation of diameters along the cutting head affects the waterjet velocity and remain constant along the nozzle tube until outlet. Turbulence is created between flow of water, air and abrasives due to high speed waterjet pressure. The vortex creates suction effects that assist transportation of abrasives particle along the nozzle tube. Particle tracking shows collision of abrasives and the wall of the nozzle wall. Pattern of erosion concentration was observed along the nozzle tube. Erosion rate and abrasives velocity were conducted against parameters of abrasive shape factor and flow rate. The simulation was validated by previous research through theoretical formulations and consistent results.

Acknowledgment

The authors would like to gratefully acknowledge the financial support from the Ministry of Higher Education, Malaysia through FRGS/1/2014/TK01/UMP/02/6.

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