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Paper

EFFECT OF DIAMETER RATIO, VOLUME FRACTION AND ABRASIVE GRAIN SIZE ON THE EXIT VELOCITY BY NUMERICAL SIMULATION OF FLOW THROUGH ABRASIVE WATER SUSPENSION JET NOZZLE USING DOE

Deepak D[1] **Anjaiah Devineni**[2] **N. Yagnesh Sharma**[3]
Manipal Institute of Technology, Manipal University
Manipal-576104, Karnataka, India.

ABSTRACT

In the present work, the diameter ratio of the nozzle and particle size of the abrasive material is taken in a parametric way to assess the effect of the same on the exit velocity of the nozzle. The abrasive particles moving with the flow causes severe wall shear, there by altering the nozzle diameter and the exit flow velocity. In consideration of this aspect, numerical simulation of the slurry flow in the nozzle is carried out to find effect of abrasive particle size and diameter ratio of nozzle on the exit velocity. The statistical experimental design technique is used to plan the simulation and analyse the simulated data. The simulation results show that, the exit velocity increases with the increase in abrasive particle size for the same diameter ratio, but the exit velocity decreases with the increase in diameter ratio.

1 Introduction

Advances in engineering materials and product design require the development of non-traditional machining processes. Components with complex shapes that need to be produced from harder and difficult-to-machine materials can now be machined by a relatively recent non-traditional method called Abrasive Water Jet (AWJ) Machining which is developed over last two decades. Abrasive water suspension jet (AWSJ) is one of variants of Abrasive water jet machining where abrasives are premixed with a suspended liquid to form slurry. The slurry is pressurized and expelled through a nozzle in AWSJ process. Advantages of AWSJ over AWJ are higher power density, no jet expansion and efficient energy transfer to abrasive particles (D. Anjaiah et. al, 2003 and T. Nguyen et. al 2003). An AWSJ can effectively machine delicate materials because of the relatively small cutting forces and lesser heat dissipation. Through computer numerical control attachment, it is possible to cut complex profiles with good surface quality and precision using AWSJ (M. Hashish, 1994).

It is to be understood that variation in the nozzle diameter ratio, size and quantity of the abrasive particles in the flow will correspondingly effect the jet exit velocity. The machining capability of the jet depends on the exit jet velocity. In the present work, the diameter ratio of the nozzle, particle size and volume fraction of the abrasive material in the flow mixture are investigated to assess the effect of the same on the exit jet velocity using numerical simulation. Simulation has been carried out using the Design of Experiments (DOE) to study the combined effect the above factors. DOE technique consists of a plan of experiments with the objective of acquiring data in a controlled way, in order to obtain information about the behaviour of a process. The simulated results have been analysed using analysis of variance (ANOVA) to determine the effect of the various input parameters on the exit velocity.

Nomenclature

DF Degrees of freedom
d Focus tube diameter
D Inlet diameter of nozzle
d_p Diameter of abrasive particles
F Fishers test value
F_s External body force
F_{Lift} Lift force
F_{vm} Virtual mass force
K Momentum exchange co-efficient
MS Mean square
SS Sum of squares
m Mass flow rate of mixture m^3/s
α Volume fraction of the phase
ρ Density of suspension mixture kg/m^3

Subscripts
p, q phases
l liquid phase
s solid phase

2 Theoretical formulations

2.1 Problem statement and assumptions

The flow domain consists of a nozzle as shown in Fig 1. Abrasive water suspension mixture is supplied at the inlet of the nozzle. Based on experimental observation (G. Hu et.al, 2008) on liquid-solid (two-phase) flow in the jet, the following assumptions are made.

- Water is a continuous medium and incompressible.
- Flow is considered as two phase mixture in which water is the liquid phase and abrasives of equal diameter constitute the solid phase, but well mixed with the liquid phase.
- There is no mass transfer between the two phases.
- Two-phase flow is steady and it possesses turbulent flow characteristics.

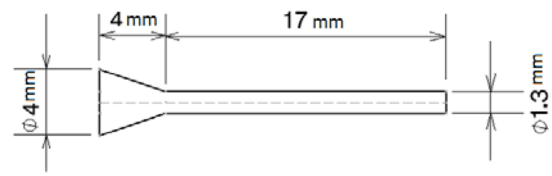

Fig.1 Geometry of the AWSJ nozzle

2.2 Numerical model

Numerical simulation was carried out using Eulerian multiphase model which is in built in the commercially available software. The governing partial differential equations, for mass and momentum are solved for the steady incompressible flow. The velocity-pressure coupling has been effected through the phase coupled SIMPLE algorithm (Semi Implicit Method For Pressure-Linked Equations) developed by Patankar S.V et.al (1972). First order upwind discretization scheme was chosen for the convective terms. Turbulence is modelled using standard k-ε turbulence model as the preferred model. The simulated results are more accurate for the high Reynolds number flow as occurs in the present study.

2.2.1 Continuity equation

The volume fraction of each phase is calculated from the continuity equation:

$$\frac{1}{\rho_{rq}}\left(\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla\bullet\left(\alpha_q\rho_q v_q\right)\right)=\sum_{p=1}^{n}\left(m_{pq}-m_{qp}\right) \tag{1}$$

2.2.2 Fluid-Solid momentum equation

Fluent uses a multi-fluid granular model to describe the flow behaviour of a fluid-solid mixture. The solid phase stresses are derived by making an analogy between the random particle motion arising from particle-particle collisions and the thermal motion of molecules in a fluid, taking into account of inelasticity of the granular phase. Intensity of the particle velocity fluctuations determines the stresses, viscosity and pressure of the solid phase. The kinetic energy associated with the particle velocity fluctuations is represented by granular temperature which is proportional to the mean square of the random motion of particles.

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

$$\frac{\partial}{\partial t}\left(\alpha_s \rho_s v_s\right) + \nabla \bullet \left(\alpha_s \rho_s v_s v_s\right) = -\alpha_s \nabla p - \nabla p_s + \nabla \bullet \tau_s + \alpha_s \rho_s g + \sum_{l=1}^{N} (k_{ls} \left(v_l - v_s\right)$$

$$+ (m_{ls} v_{ls} - m_{sl} v_{sl}) + (F_s + F_{lift,s} + F_{vm,s}) \quad (2)$$

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

$$\frac{\partial}{\partial t}\left(\alpha_q \rho_q v_q\right) + \nabla \bullet \left(\alpha_q \rho_q v_q v_q\right) = -\alpha_q \nabla p + \nabla \bullet \tau_q + \alpha_q \rho_s g + \sum_{p=1}^{N} (k_{pq} \left(v_p - v_q\right)$$

$$+ (m_{pq} v_{pq} - m_{qp} v_{qp}) + (F_q + F_{lift,q} + F_{vm,q}) \quad (3)$$

3. Method of solution

3.1 Numerical scheme

The particles were assumed to be spherical and uniformly distributed in the suspension mixture. Conservation equations were solved for each control volume to yield the velocity and pressure fields. Convergence was effected when all the residuals fell below $1.0E^{-5}$ at all control volume in the computational domain. Computational domain was modelled using the pre-processor routine called GAMBIT and meshing was also done using appropriate grid cells of suitable size available in the routine. Wall region in the flow domain was fine meshed using the boundary layer mesh concepts for extracting high velocity gradients near the boundary walls. According to the geometry of nozzle and jet characteristics, computational domain is built as axi-symmetric model. The solution domain consists of 8460 cells of Quad type. The grid independence test was performed to check validity of the quality of mesh on the solution. The influence of further refinement did not change the result by more than 1.25 % which is taken here as the appropriate mesh quality for computation.

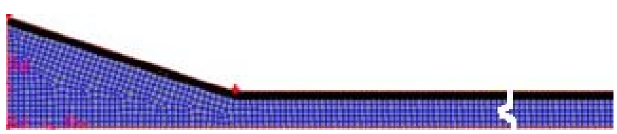

Fig.2 Mesh of the computational domain

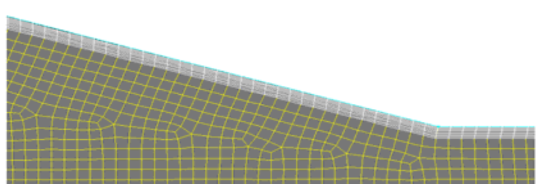

Fig.3 Closer view of the mesh near converging section

3.2 Boundary conditions and Operating parameters

Appropriate boundary conditions were impressed on the computational domain, as per the physics of the problem. Inlet boundary condition was specified as velocity boundary condition. Average velocity of AWSJ at inlet was calculated using mass flux equation.

$$\dot{m}_{in} = 0.25\rho\pi d^2 u \qquad (4)$$

The velocity distribution is considered as plug flow at inlet. Pressure outlet boundary condition was applied at the outlet with static pressure of flow taken as zero, so that the computation would yield relative pressure differences for the entire domain of the flow. Wall boundary conditions were used to bound fluid and solid regions. In viscous flow models, at the wall, velocity components were set to zero in accordance with the no-slip and impermeability conditions that exist there. Center line of the nozzle is considered as axis of nozzle and hence symmetry boundary condition was applied at the axis.

In Numerical simulation, mixture of water and suspension liquid is treated as Phase 1 and Garnet abrasive as Phase II. The input parameters used in the analysis are as shown in the table 1 below.

Table 1. Input parameters (G. Hu et.al, 2008).

Parameter	**Set value**
velocity of mixture	25.6m/s
Density of Phase I	998.2 kg/m^3
Density - Phase II	2300 kg/m^3
Viscosity - Phase I	0.001003kg/(m.s)
Viscosity - Phase II	1.7894e-^{05} kg/(m.s)
Slip of phases	no slip

3.3 Experimental Design for numerical simulation

Full factorial design has been chosen for numerical simulation. The factors and their levels used in the present numerical simulation are given in the table 2. The numerical simulation has been carried out as per the experimental design and the corresponding simulated results are shown the table 3.

Table 2. Factors and their levels (D.Anjaiah, et.al, 2009)

Factors	Level 1	Level 2	Level 3
Diameter ratio	0.25	0.325	0.375
Abrasive grain size (Micron)	100	125	190
Volume fraction (%)	5	10	15

Table 3 Experimental design with simulation results

Trial	Diameter ratio	Abrasive size (Microns)	Volume fraction (%)	Exit velocity (m/s)
1	0.250	100	5	425.56
2	0.250	100	10	426.70
3	0.250	100	15	427.45
4	0.250	125	5	422.94
5	0.250	125	10	424.06
6	0.250	125	15	425.00
7	0.250	190	5	416.67
8	0.250	190	10	417.94
9	0.250	190	15	419.31
10	0.325	100	5	249.41
11	0.325	100	10	250.36
12	0.325	100	15	250.94
13	0.325	125	5	247.76
14	0.325	125	10	248.77
15	0.325	125	15	249.47
16	0.325	190	5	243.92
17	0.325	190	10	245.13
18	0.325	190	15	246.00
19	0.375	100	5	186.68
20	0.375	100	10	187.47
21	0.375	100	15	187.97
22	0.375	125	5	185.31
23	0.375	125	10	186.16
24	0.375	125	15	186.75
25	0.375	190	5	182.29
26	0.375	190	10	183.38
27	0.375	190	15	184.20

3 Results and discussions

The data collected from the simulation has been analysed using ANOVA with the help of MINITAB software. The ANOVA results in table 4 shows the effect of input factors on the exit velocity. It is observed from the same table that the diameter ratio is significantly effecting the exit velocity and its contribution towards the variation of the exit velocity is found to be maximum (99.92 %).

Table 4. ANOVA results

Source	DF	SS	MS	F	% SS
Dia Ratio	2	272304	136152	148298.68	99.92
Abr Size (Microns)	2	168	84	91.35	0.06
Volume fraction (%)	2	15	8	8.44	0.00
Error	20	18	1		
Total	26	272506			

It is observed from the figure 4 that the exit velocity decreases with increase in diameter ratio. This trend may be explained by the fact that for a given nozzle inlet diameter as the focus tube diameter increases there is a decrease in exit velocity of the jet. It is observed from the figure 5 that the effect of abrasive size and volume fraction on exit velocity is very small. For the particles of finer diameter, the inertial effect of mass of the abrasive particles on the flow is insignificant and hence do not contribute to any significant changes in the velocity of the particle. Hence during the experimentation the abrasive size and volume fraction can be kept constant at suitable level.

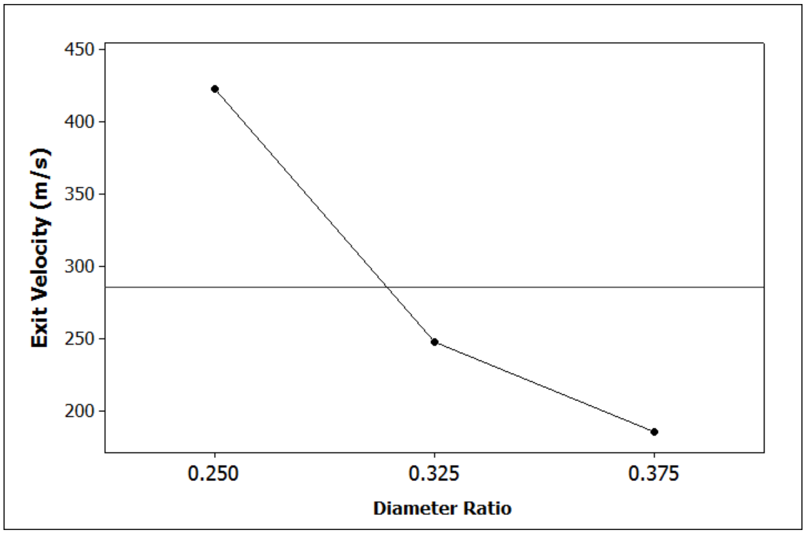

Fig 4. Effect of Diameter ratio on exit velocity

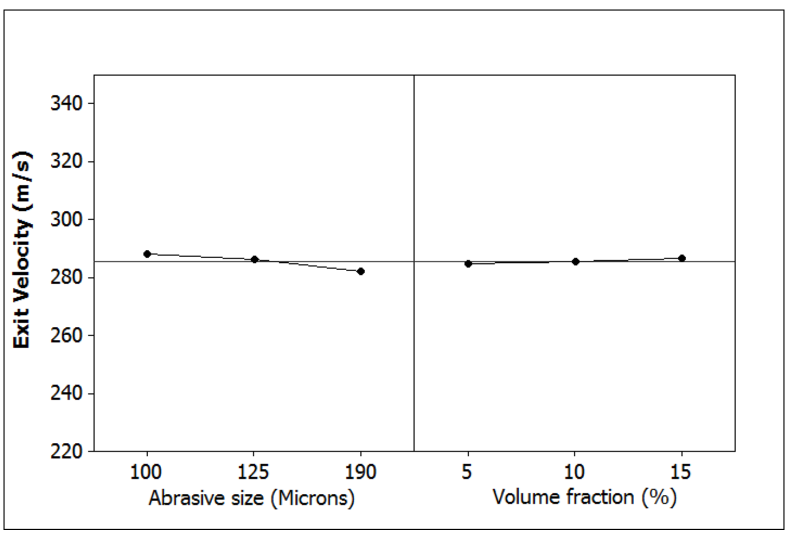

Fig 5. Effect of abrasive size and volume fraction on exit velocity

Conclusion:

The following conclusions have been drawn from the present work.

- Numerical simulation method may be considered as a preliminary tool to identify the important input parameters before conducting actual experimentation.
- As the diameter ratio increases the exit jet velocity decreases correspondingly.
- Effect of abrasive size and the volume fraction on exit velocity is very small which may be neglected.

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References

[1] D.Anjaiah, A.M Chincholkar and B. Siddeswarappa, "Effect Of Process Parameters On The Material Removal Rate On Glass In Low Pressure Abrasive Slurry Jet Machining", in Proc. of National Conference on World class manufacturing, India, 2003, pp 20-24.
[2] D.Anjaiah and A.M Chincholkar, "AWSJ Cutting Of Ceramics – An Experimental Study Of The Effect Of Process Parameters On The Surface Roughness Using DOE", in Proc. of 9th Pacific Rim International Conference on Water Jetting Technology, Nov 20-23, 2009.
[3] G.J. Brown, "Erosion Prediction In Slurry Pipeline Tee-Junctions", Applied mathematical modelling, vol. 26, 2002, pp.155-170.
[4] Fluent user's guide, Volume I to IV
[5] B.K.Gandhi, "Study Of The Parametric Dependence Of Erosion Wear For The Parallel Flow Of Solid –Liquid Mixtures", Tribology International, vol.32, 1999, pp.275-282.
[6] L.J.Graham, D. Lester, and J. Wu, "Slurry Erosion In Complex Flows : Experiment and CFD", Seventh International Conference On CFD In The Minerals And Process Industries, CSIR, Melbourne, Australia, 2009,pp.1-6.
[7] M.Hashish, "Observations Of Wear Of Abrasive Waterjet Nozzle Materials", Journal of Tribology, Vol-116, 1994, pp. 439-444
[8] G. Hu, W. Zhu, T. Yu, and J. Yuan, "Numerical Simulation and Experimental Study of Liquid-solid Two-phase Flow in Nozzle of DIA Jet", Proceedings of the IEEE International conference industrial informatics(INDIN 2008), Daejeon, Korea, July 13-16th 2008.
[9] M. Nanduri, D.G. Taggart, and T.J. Kim, "The Effects Of System And Geometric Parameters On Abrasive Water Jet Nozzle Wear", Wear, vol. 42, 2002, pp. 615-623.
[10]T. Nguyen, D.K. Shanmugam and J. Wang, "Effect Of Liquid Properties On The Stability Of An Abrasive Waterjet", International Journal of Machine Tools and Manufacture, Volume 48, Issue 10, pp 1138-1147, 2008.
[11]A.C. Phase and C. Equation, "Numerical Simulation on Flow Field of Pre-mixed Abrasive Water Jet Nozzle", IEEE-2008 Asia Simulation Conference-7th Intl. Conf. on Sys. Simulation and Scientific Computing, 2008, pp. 247-251.
[12]Patankar S.V. and D.B. Spalding, "A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows", International Journal of Heat Mass Transfer, 1972, vol. 15, p. 1787
[13]Z. Shangxian, L. Yan, W. Quan, B. Discretization, and G. Space, "Track Calculation and Numerical Simulation on Particles in High Pressure Abrasive Water Jet Nozzle", IEEE International Conference on Measuring Technology and Mechatronics Automation 2010, pp. 1039-1042.