Numerical Analysis of Flow through Abrasive Water Suspension Jet: The Effect of Inlet Pressure on Wall Shear and Jet Exit Kinetic Energy

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Abstract: It is well known that the inlet pressure of the abrasive water suspension has significant effect on the erosion characteristics of the inside surface in the nozzle. Abrasive particles moving with the flow causes severe wall shear, there by altering the nozzle diameter due to wear which in turn influences the jet kinetic energy. This will reflect on the life of the nozzle for effective machining. In consideration of this aspect, in the present work, the effect of inlet pressure on wall shear stress and jet kinetic energy is considered and analysed. It is found from the analysis that an increase in inlet pressure results in significant increase in the wall shear stress induced. Also an increase in inlet pressure results in proportional increase in the jet kinetic energy.

Keywords: Abrasive Water Suspension Jet, Jet Exit kinetic energy, Wall Shear

I. INTRODUCTION

Recent research trends in engineering product design and processes underscore development of non-traditional machining methods. Machine parts with complex shapes that need to be produced from harder and difficult-to-machine materials can now be machined by a relatively new non-traditional method called Abrasive Water Jet (AWJ) Machining. Abrasive water suspension jet (AWSJ) is one of the variants of Abrasive water jet machining where abrasives are premixed with a suspended liquid to form a slurry. The slurry is pressurized and expelled through the nozzle in AWSJ process. Advantages of AWSJ over AWJ are due to higher power density, no jet expansion and efficient energy transfer to abrasive particles [6,8,10]. An AWSJ can effectively machine delicate materials because of the relatively smaller 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 [2].

The general nature of flow through the AWSJ, results in rapid wear of the nozzle which degrades the cutting performance. Nozzle replacement costs play a significant role in the economics of the machining process and improvements in its wear characteristics, are critical for the growth of AWSJ technology [5]. A host of articles are available on both the experimental and numerical aspects of flow through the AWSJ nozzle [3, 4, 9, 11, 12, 13]. Recently with the development of CFD general purpose code it has become possible to model and simulate the flow through the AWSJ nozzle in a more realistic manner, using two phase Eulerian flow model.

It is interesting to evaluate the effect of the variation of inlet pressure of the abrasive water suspension, on the wall shear stress of the nozzle as well as on the exit jet kinetic energy. It is to be understood that due to relatively high pressure used, in the order of 600 Bar, the jet velocity correspondingly becomes quite high. The abrasive particles moving with the corresponding high velocity of flow cause severe wall shear. This causes erosion of the nozzle, due to which the effective diameter of the nozzle may change significantly resulting in reduced exit kinetic energy of the jet. This will not only reflect on the life of the nozzle but also the reduced kinetic energy will affect the machining process. In consideration of this aspect, in the present work not only the effect of inlet pressure of abrasive water suspension on the wall shear is considered and analysed but also the effect of inlet pressure on jet kinetic energy is examined.

Nomenclature

d	Focus tube diameter
D	Inlet diameter of nozzle
F_{Lift}	Lift force
F_s	External body force
F_{vm}	Virtual mass force
K	Momentum exchange co-efficient
$\dot{m}$	Mass flow rate of mixture m^3/s
V	Velocity of phase

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α	Volume fraction of the phase
ρ	Density of suspension mixture kg/m^3
d_p	Diameter of abrasive particles

Subscripts

p, q	phases
l	liquid phase
s	solid phase

II.

III. THEORETICAL FORMULATIONS

Problem statement and assumptions

The problem taken up in this paper pertains to finding the effect of inlet operating pressure on wall shear as well as jet exit kinetic for flow through abrasive water suspension jet.

The flow domain consists of a nozzle connected to the focus tube as shown in figure 1. Abrasive water suspension mixture is supplied at the inlet of the nozzle. Based on experimental observation on liquid-solid (two-phase) flow in the jet, the following assumptions are made.

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

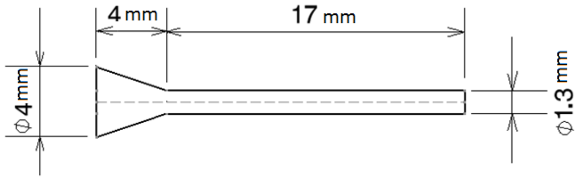

Fig.1 Geometry of the AWSJ nozzle

Numerical model

Numerical simulation was carried out using Eulerian multiphase model which is an 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 [1]. Power law and QUICK schemes were chosen for the solution schemes. Turbulence is modelled using Realizable k-ε turbulence model for proper convergence. The simulated results are more accurate for the high Reynolds number flow as occurs in the present study.

Continuity equation

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

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

Fluid-Solid momentum equation

Fluent uses a multi-fluid granular model to describe the flow behavior 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 the 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 [14].

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

$$\frac{\partial}{\partial t}\left(\alpha_s\rho_s v_s\right)+\nabla\bullet\left(\alpha_s\rho_s {v^2}_s\right)=-\alpha_s\nabla p-\nabla p_s+\nabla\bullet\tau_s+\alpha_s\rho_s g$$
$$+\sum_{l=1}^{N}\left[k_{ls}\left(v_l-v_s\right)+\left(m_{ls}v_{ls}-m_{sl}v_{sl}\right)\right]$$
$$+\left(F_s+F_{lift,s}+F_{vm,s}\right) \qquad (2)$$

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

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q v_q\right)+\nabla\bullet\left(\alpha_q\rho_q v_q^2\right)=-\alpha_q\nabla p+\nabla\bullet\tau_q+\alpha_q\rho_s g$$
$$+\sum_{p=1}^{N}\left[k_{pq}\left(v_p-v_q\right)+\left(m_{pq}v_{pq}-m_{qp}v_{qp}\right)\right]$$
$$+\left(F_q+F_{lift,q}+F_{vm,q}\right) \qquad (3)$$

IV. METHOD OF SOLUTION

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^{-3} 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 were fine meshed using the boundary layer mesh concepts for extracting high velocity gradients near the boundary walls. According to the structure of nozzle and jet characteristics, computational domain is built as axi-symmetric model. Figure 2 and Figure 3 show the computational domain. 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.

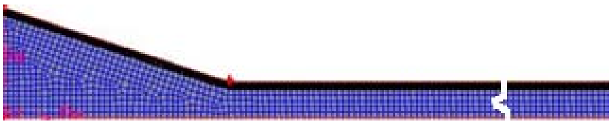

Fig.2 Mesh of the computational domain

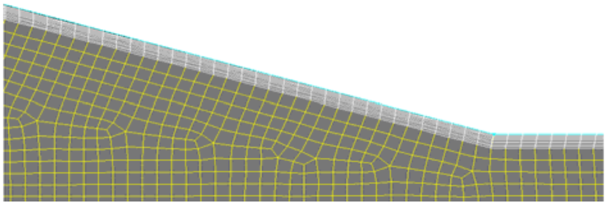

Fig.3 Closer view of the mesh near converging section

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 Pressure inlet condition. 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 abrasive as Phase II. The input parameters used in the analysis are as shown in the table 1 below.

Table 1. Input parameters for simulation [7].

Parameter	Value
Volume fraction	10 %
Density - Phase I (Suspension Liquid)	998.2 kg/m^3
Density - Phase II (Garnet abrasive)	2300 kg/m^3
Viscosity - Phase I	0.001003kg/(m.s)
Viscosity - Phase II	1.7894e-05 kg/(m.s)
Size of abrasive	0.1mm
Slip of phases	no slip

V. RESULTS AND DISCUSSION

Validation of the numerical model

To establish validation of the present model, the work cited in reference [7] was used to replicate the velocity distribution as obtained by them (Figure 4) with the existing numerical model adopted in this work (Figure 5).

The graph of the velocity distribution of one of the phases (Liquid phase) has been calibrated in the present work with that of the work cited in the literature as shown in figure 4. It is clear that there is good agreement between the two models as regards to the velocity distribution.

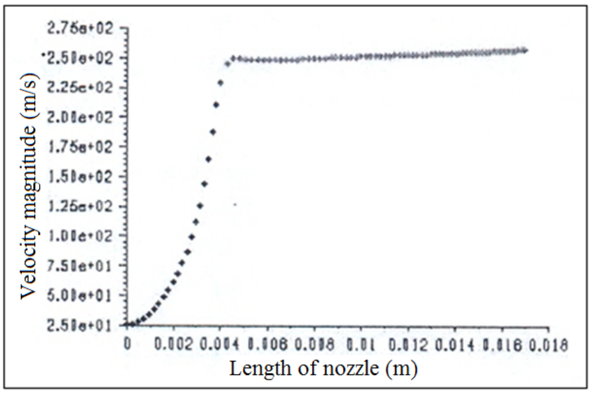

Fig 4. Plot of Velocity[7]

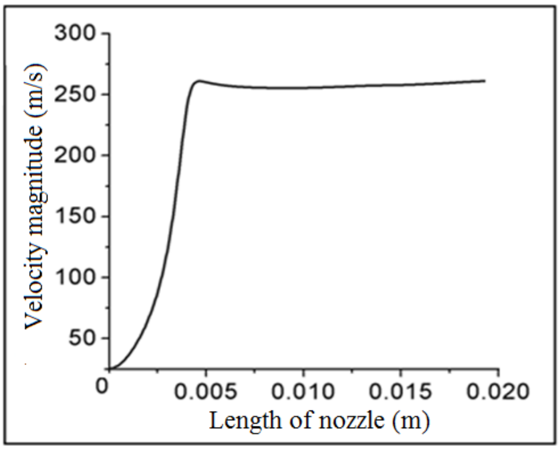

Fig 5. Plot of Velocity as per the present model

Effect of inlet operating pressure on wall shear stress:

It is found from the plot of wall shear stress developed along the length of the nozzle corresponding to various inlet operating pressure conditions that, there is direct relationship between wall shear stress and inlet pressure. As seen from figure 6, higher the operating pressure, higher will be the wall shear stress developed all along the nozzle. This is true because in the nozzle, the pressure energy is converted to kinetic energy and hence increased velocity is manifested all along the converging duct which results in higher wall shear stress, due to higher velocity gradients. For any given inlet operating pressure the wall shear stress initially increases in the converging section of the nozzle.

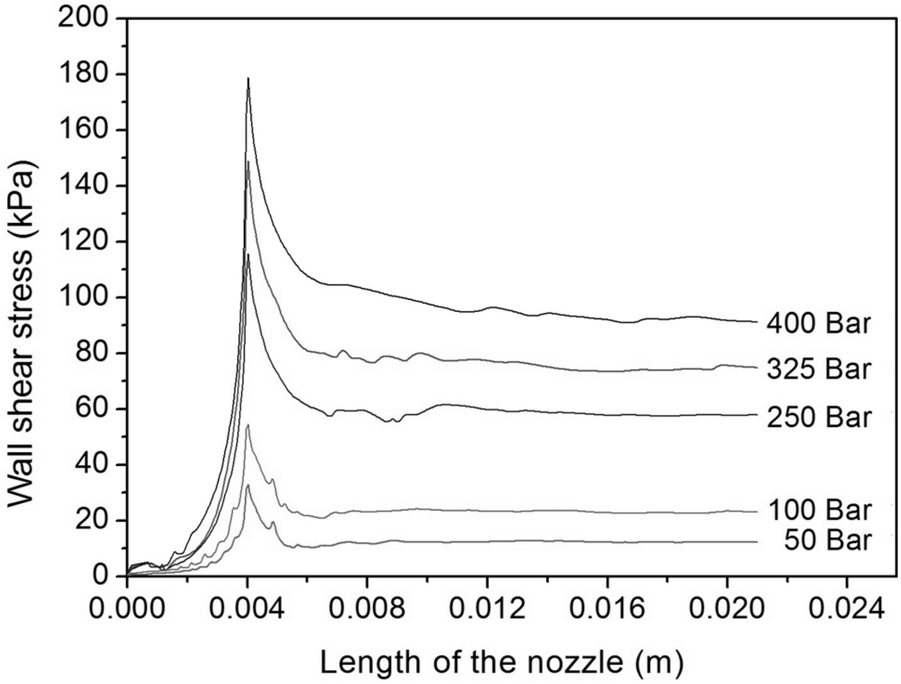

Fig. 6: Plot of wall shear stress along the length of the nozzle

However the wall shear stress seems to peak near the critical section which is due to a sudden change in the velocity gradient corresponding to the change in area at the critical section. But the wall shear stress seems to attain near constant value along the focus tube as there is no significant velocity change in the constant diameter focus tube till the exit of the nozzle.

It is also seen from the graph that the velocity gradients will have slight instability when changing over from converging duct portion to straight duct portion of the nozzle as can be seen from the wiggles in the shear stress distribution curves in the vicinity of the critical section.

Effect of inlet pressure on average exit kinetic energy of the jet

It is seen from the graph shown in figure 7 that the useful average kinetic energy of the jet is linearly proporational to inlent operating pressure.

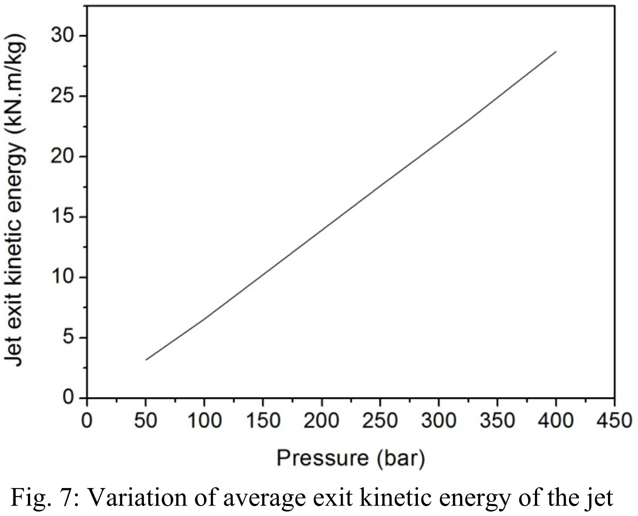

Fig. 7: Variation of average exit kinetic energy of the jet with inlet operating pressure

This is due to the fact that, from the conservation of energy principles, inlet operating pressure energy should manifest as proportional amount of kinetic energy at the exit of the nozzle with viscous shear stress dissipation being also proportional to inlet operating pressure conditions which is as shown in figure 8.

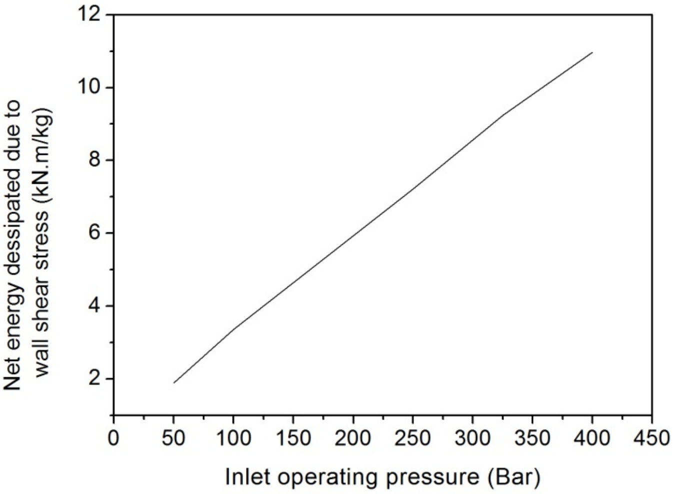

Fig. 8: Plot of net energy dissipated due to wall shear stress with respect to inlet operating pressure

Average exit kinetic energy is computed with area weighted average over the control volume at the exit of the nozzle. The energy dissipated due to wall shear is computed from work done by the shear forces on the surface of the nozzle. the abrasive particles moving with flow causes severe wall shear which causes erosion. This leads to erosion of the inside surface of the nozzle resulting in decreased jet kinetic energy, there by affecting the performance of the nozzle for effective machining.

VI. CONCLUSION

The following conclusions are deduced from the above numerical simulation:

- Increase in inlet operating pressure results in significant increase in the wall shear stress.
- The wall shear stress approach peak values corresponding to the sudden change in the flow passage geometry at the critical section as shown in figure 6.
- Increase in the inlet operating pressure results in linear increase in the average exit kinetic energy of jet.

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