Computational Optimization of Water Jet Machining: Effect of Nozzle Jet Diameter Ratio

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Abstract - *In this paper focuses on the computational analysis of a water jet (WJ) machining. For this a computational model of water jet machining has been simulated by using ANSYS Fluent. A CAD model of nozzle has been developed by using geometrical model of ANSYS. During analyzing the effect operating pressure and nozzle parameter has examined. The effect of nozzle jet diameter ratio has been observed on nozzle turbulent intensity, skin friction coefficient and velocity magnitude. The validated the obtained finite volume results a comparison has been made with previous available literature and the result are showing good trend.*

Key Words: *Jet diameter ratio, skin friction, Turbulence Intensity*.

1. INTRODUCTION

Water jet cutting have a considerable niche in the material processing industry. Like laser cutting instruments they are accurate, easily managed and cause very little loss of material. However, abrasive jet cutting does not involve high temperatures, which is characteristic to laser cutting, and as a result they are suitable for practically any material. Furthermore, the instrumentation required for high-speed jets is simpler and much cheaper. Consequently, jet cutting can be implemented in a broad range of industries, ranging from small machine shops and quarries, to large sheet metal, composites or ceramic processing in the car and aircraft industries.

2. LITERATURE REVIEW

Shiou and Asmare 2015, presents surface roughness improvement of Zerodur optical glass by means of an innovative rotary abrasive fluid multi-jet polishing process. Even though tauguchi approach has also been implement. It has observed that 98.33% improvement in surface roughness has been achieved and the factors effecting the surface roughness has also been discussed.

Wang et al.2014 conducts experimental investigate to explore the effect of different process parameters such as jet impact angle, standoff distance, water pressure, abrasive particle diameter on material removal rate, removal depth and surface roughness for hard and brittle material, the alumina ceramic are used as base material.

Baisheng et al. 2011, perform numerical simulation for inside flow field and outside high pressurized AWJ nozzle using ANSYS fluent. The obtained result shows that shock zone and wall jet zone in the external flow field of nozzle, there exist free jet zone; the section of abrasive jet farther from the target wall is of free jet structure; the shock pressure field on the target wall is standard distribution; the best shock range is 2-7 times the exit diameter of nozzle; the shock pressure of jet is proportional to the inlet pressure, and is inversely proportional to the range.

Anwar et al. 2013, use finite element (FE) method for AWJ foot print in which modelling, simulation and validation has been done for various transverse speed and pump pressure. The obtained result of material removal rate is compared with experimental data and the profile of kerf formation has also been examined.

Radim et al. 2013, investigates the cut wall during AWJ process of non-corroding steels treated by cryogenic temperatures in liquid nitrogen. They reveal that the cryogenic temperatures significantly influence the material structure and respective properties. The main aim of their work is to enhance the material reliability in a wide range of production systems and operation conditions.

Liu et al. 2004, using CFD an ultrahigh velocity waterjets and abrasive waterjets (AWJs) model has been modeled using Fluent. The model consist of 2 and 3 phase flow condition in which water and abrasive particle where allowed to flow at different velocity and volume fraction.

Axinte et al. 2010, presents a geometrical model of the jet footprint (kerf) in maskless controlled-depth milling applications. The model firstly capable to evaluate the material specific erosion (etching) rate that is attained from the jet footprint by taking the limiting conditions (high jet feed rates) of the model. Once this is found, the jet footprint can be predicted accurately for any jet feed speed.

Wan and lim 2003, analyze transient flow in abrasive suspension jet cutting machines. The effort has been made in order to explore the problem of line and nozzle clogging, which would be overcome by the higher operating pressures and the employing smaller nozzles for fine-beam systems.

Chen and siores 2003, investigates the characterization of different materials' cut surfaces using a scanning electron microscope. The effect of abrasive particle distribution in the jet on striation development has discussed and examined by means of laser Doppler anemometry.

Hassan and kosmol 2001, develop a FEM model for AWJM in explain the work piece- abrasive particle interaction. The model can predict the depth of deformation consequently due to abrasive particle impact. The main aim of the develop model is to predict the depth cut without performing experimentation. In the results the dynamic behavior of the AWJ has been explored and the results are compared with the experimental work and shows good consistency.

Soiores et al. 1996, optimize the AWJ cutting technology for ceramics, experimentally by using statistical design principles. A new cutting head oscillation technique has been employed and it has found that the cutting quality improves by 30%.

El-domiaty an rahman 1997, developed abrasive waterjet model using two elastic-plastic erosion models. The model is valid only for brittle material. The model has ability to predict depth of maximum depth of cut on the basis of fracture toughness and hardness. Moreover, parametric analysis has also been carried in order to investigate the parameter affect on maximum depth of cut.

Wang 2002, develop a semi empirical model for abrasive water jet (AWJ) cutting of composite layered materials. During cutting of laminates, it starts delaminating form layer to layer, which results in failure of cutting process. Using the developed model, the depth of jet penetration can be determined and the performance can be enhanced during cutting process.

3. MATHEMATICAL MODELLING

In system water jet machining is been analyzed with different aspect ratio. The wall shear stress is analyzed during cuting process and the effect of nozzle jet diameter ratio has also examined, in additional to varying the orientation also the heat transfer and shear stress is taken in consideration with the wall surface of the nozzle.

The equations governing this problem are those of Navier-Stokes along with the energy equation. The Navier-Stokes equations are applied to incompressible flows and Newtonian fluids, including the continuity equation and the equations of conservation of momentum on the x and y

According to equations

$$\frac{\partial u_2}{\partial t} + u_1 \frac{\partial u_1}{\partial x_1} + u_2 \frac{\partial u_1}{\partial x_2} =$$

$$-\frac{1}{\rho}\frac{\partial \rho}{\partial x_2} + \nu\left(\frac{\partial^2 u_1}{\partial x_1^2} + \frac{\partial^2 u_1}{\partial x_2^2}\right) + g\beta(T - T\infty)$$

$$\frac{\partial u_1^*}{\partial x_1^*} + \frac{\partial u_2^*}{\partial x_2^*} = 0$$

x1 momentum equation

$$\frac{\partial u_1^*}{\partial t^*} + u_1^* \frac{\partial u_1^*}{\partial x_1^*} + u_2^* \frac{\partial u_1^*}{\partial x_2^*} = -\frac{\partial p^*}{\partial x_1^*} + \Pr\left(\frac{\partial u_1^*}{\partial x_1^*} + \frac{\partial u_1^*}{\partial x_2^*}\right)$$

x2 momentum equation

$$\frac{\partial u_2^*}{\partial t^*} + u_1^* \frac{\partial u_2^*}{\partial x_1^*} + u_2^* \frac{\partial u_1^*}{\partial x_2^*} = -\frac{\partial p^*}{\partial x_2^*} + \Pr\left(\frac{\partial u_2^*}{\partial x_1^*} + \frac{\partial u_2^*}{\partial x_2^*}\right)$$

$$+Gr \Pr^2 T^*$$

Energy equation

$$\frac{\partial T^*}{\partial t^*} + u_1^* \frac{\partial T^*}{\partial x_1^*} + u_2^* \frac{\partial T^*}{\partial x_2^*} = \left(\frac{\partial^2 T^*}{\partial x_1^{*2}} + \frac{\partial^2 T^*}{\partial x_2^{*2}}\right)$$

Since in order to check the accuracy of developed computational model which is coupled with Navier stokes equation and additional boundary conditions are provided through which heat transfer and mass flow, stress, etc other parameters are calculated and contour figures are generated and illustrated in the in this paper.

4. METHODOLOGY

The governing equation of water jet machining is solved by using ANSYS Fluent solver. Since it's quite complex to solve the differential equation of motion manually, therefore computational tool FEV tool has been applied to solve the governing equation. In ANSYS 14.5 computational model has been developed in geometrical section with given geometrical parameters from the base paper i.e. [7-8]. After that the geometrical model is extended to mesh section in which complete geometry of WJ is discretized into various numbers of nodes and elements i.e. (27,857 and 27,456) using mapped meshing the detail of meshing is given in figure 5.2. Moreover, the geometrical mesh model is further named such inlet, outlet, axis, wall section, etc. so that proper boundary conditions can applied in order to evaluate performance characteristics of water jet machining.

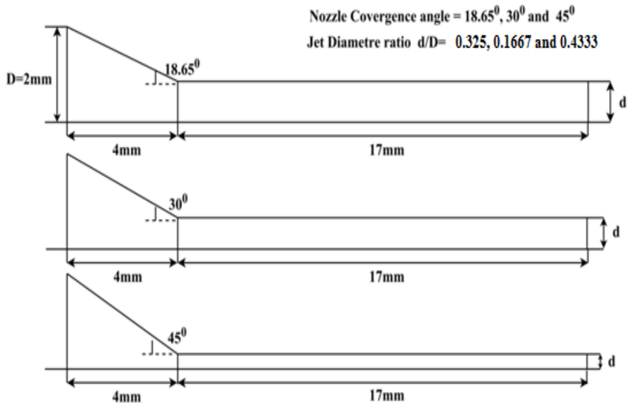

Fig. 1: Computational model detail of WJ nozzle

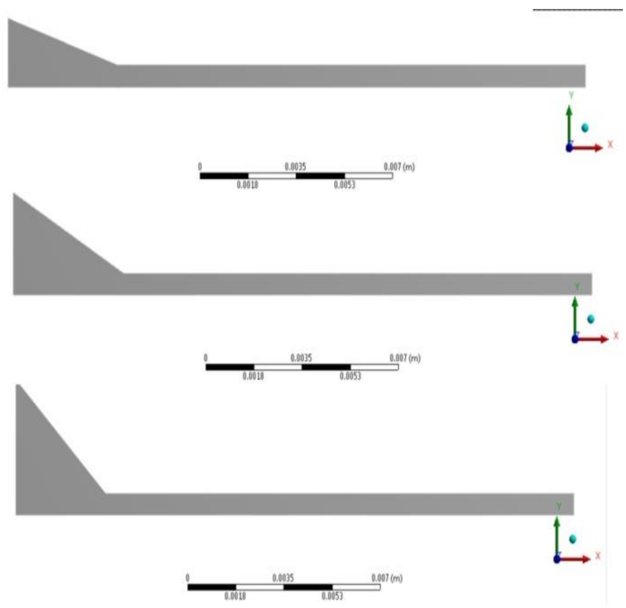

Fig. 2: Model Geometry

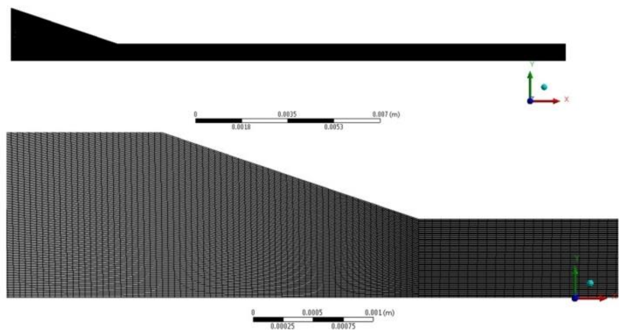

Fig. 3: Mesh computational model

Table 1 Operating parameters of water jet machining Ref. [7-8]

Parameter	**Value**	**(Proposed) Value**
Inlet Diameter	4mm	4mm
Converging angle,θ	26.56^0	30^0
Converging length	4mm	4mm
Focus tube length	17mm	18mm
Exit Diameter	1.3mm	0.65
Volume fraction	13%	7-10%
Density of primary phase	998.2kg/m^3	998.2kg/m^3
Density of secondary phase	2300kg/m^3	2300kg/m^3
Slip of Phases	No Slip	No slip
Turbulence model	k-ϵ	k-ϵ
Flow	Incompressible	Incompressible
Mode of operation	Steady state	Steady state
Stokes number	0.3552	0.3552

5. RESULTS AND DISCUSSION

The equation of motion of abrasive water jet machine is solved by using control volume approach and all the governing equation are solved by using ANSYS- Fluent solver in which all the partial differential continuity and momentum equation are solved by iterative process till all the solution gets converged.

In order to validate the present work a computational model of water jet machine has been developed and compared with the available literature of Numerical Simulation and Experimental work of Huang et al. [7-8] and found that the obtained results are within acceptable limit and showing same trend as shown in figure 4.

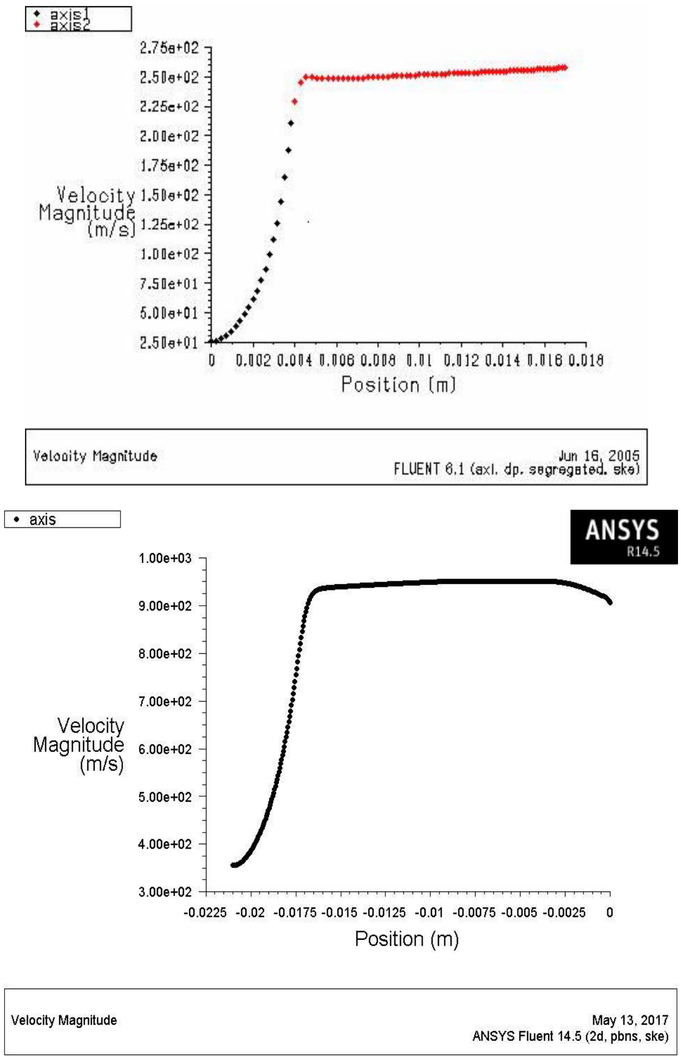

Fig. 4: Validation of present work with the Numerical Simulation and Experimental work of Huang et al. [7-8]

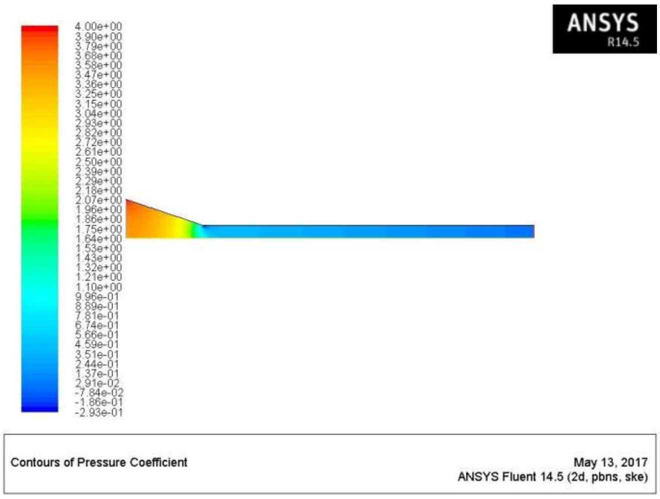

Fig - 5 : counter of pressure coefficient

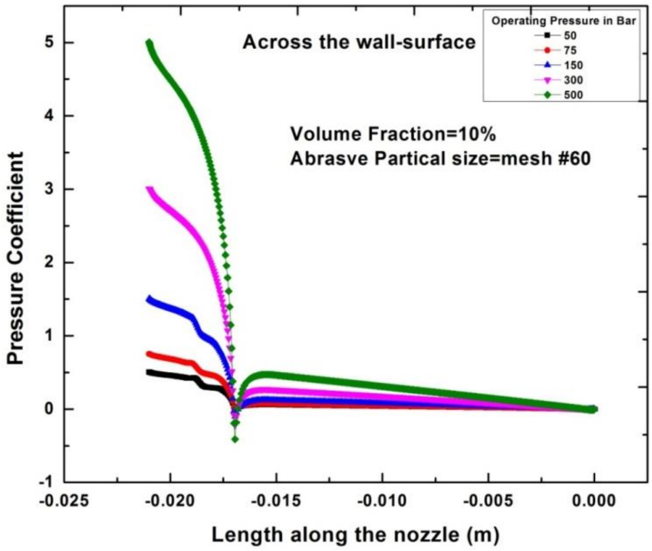

Fig – 6: Effect of operating pressure on pressure coefficient across the nozzle length

Figure 6 illustrates the effect of operating pressure on pressure coefficient across the nozzle length. It has been observed that as the operating pressure enhances the rate of pressure drop across the axis and wall surface significantly increases. It has also been scrutinized that the foremost drop in pressure across the axis and the wall surface is in the region where nozzle cross section changes i.e. from convergence region to Focal region.

From this it can be also be revealed that on changing the sudden cross section abrupt change drop in pressure takes place. The same representation has been seen in figure 5.

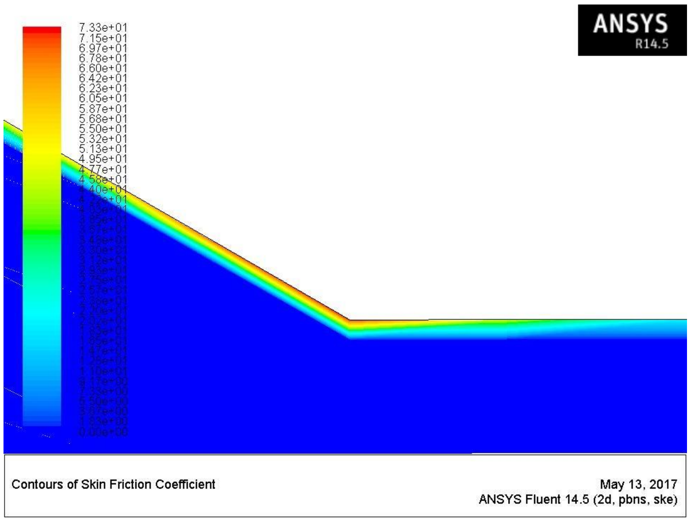

Fig- 7 : Contour of skin friction coefficient

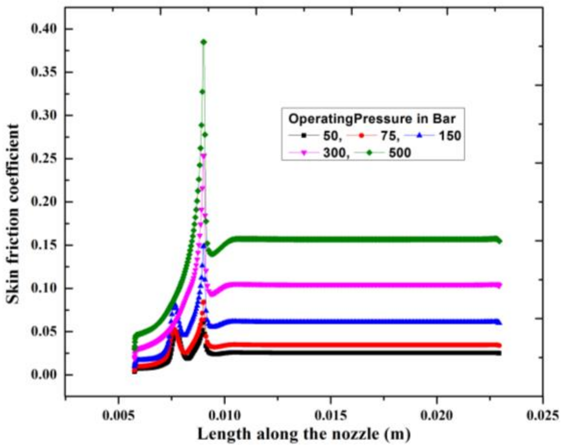

Fig- 8 : Effect of operating pressure on skin friction coefficient across nozzle length

Figure 8 effect of operating pressure on skin friction coefficient across nozzle length. It has been found that on increasing the operating pressure, skin friction coefficient drastically increases till it reaches the peak and then there is a significant drop and get constant. This is due to change in cross section from converge region to focal region. Since the skin friction coefficient is proportional to flow Reynolds number and corresponding to flow velocity.

Therefore, it can be concluded that at converge region velocity increases rapidly which results in an increase in coefficient. But the fluid flow is not fully developed in the converge region and when flow velocity changes there is a sudden decrease in skin friction due to sudden contraction which corresponded to a loss of flow energy. This can be revealed from figure 7 and it can be seen in nozzle length between 0.020-0.015. Moreover, as the operating pressure increases skin friction increases correspondingly to velocity.

Effect of jet diameter ratio

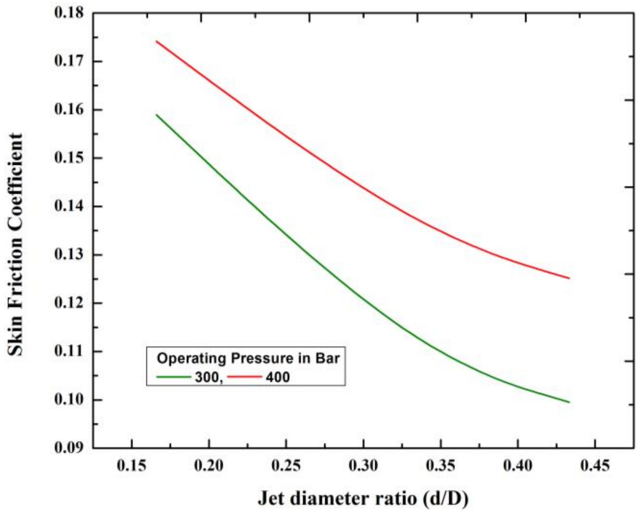

Fig- 9: Effect of jet diameter ratio on skin friction coefficient

Figure 9 shows the effect of jet diameter ratio on skin friction coefficient. It has been examined that skin friction coefficient decreases linearly as nozzle jet diameter ratio increases. Furthermore, on increasing operating pressure, the rate of decline in skin friction is more noteworthy for lower operating pressure. This is because of increase in the jet diameter ratio means the surface area increases eventually, the pressure decreases and results in decreases in skin friction.

It has also been observed that the rate of decline of skin friction coefficient at 300bar is 37.378% more significant as compared to skin friction coefficient at 400bar. However, as the operating pressure increases this rate of decline of skin friction coefficient decreases remarkably.

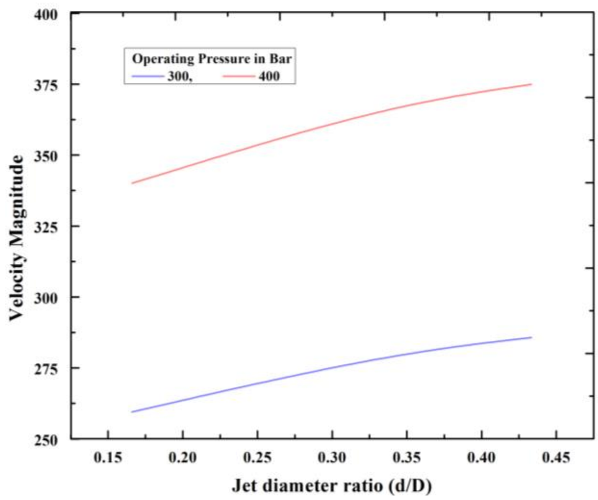

Fig -10 : Effect of operating pressure along with nozzle jet diameter ratio on velocity magnitude

Figure 10 demonstrates effect of operating pressure along with nozzle jet diameter ratio on velocity magnitude. It has seen that with increasing jet diameter ratio, the velocity linearly increases. However, also on increasing operating pressure the velocity increases. This is due to pressure is inversely proportional to velocity and at the exit velocity increases as per continuity equation Av=const as conferred by Bernoulli equation.

It can also be revealed that the velocity magnitude at 400bar is 15.98% more as compared to 300bar. Whereas, the rate of enhancement of velocity at 300bar is 4.92% and 5.69% at 400bar as jet diameter increases. From this it is clear that as the operating pressure increases this rate of enhancement of velocity significantly increases.

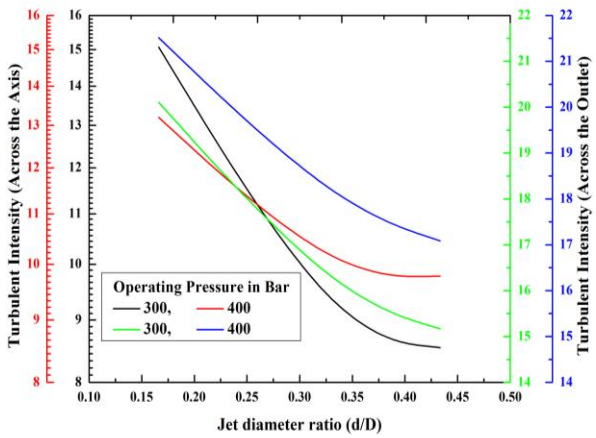

Fig – 11 : Effect of operating pressure along with nozzle jet diameter ratio on turbulent intensity across the axis and the wall surface.

Figure 11 illustrates the effect of operating pressure along with nozzle jet diameter ratio on turbulent intensity across the axis and the wall surface. It has been seen that the turbulent intensity across the axis decreases significantly as increasing jet diameter ratio of nozzle. It has been also found that the rate of decrease in turbulent intensity across the axis decreases as operating pressure increases. It has been also concluded that at higher values of the jet diameter ratio the turbulent intensity across the axis get constant. But across the outlet the turbulent intensity decreases continuously.

6. CONCLUSION

Cutting velocity of the nozzle increases as operating pressure increases

As operating pressure increases, the skin friction coefficient increases. At the critical region i.e. region between convergence and focal region the skin friction coefficient reaches its maximum value and sudden decrease has been seen after that and gets constant in focal region of the nozzle.

At the critical region, the turbulent intensity within nozzle is maximum and as operating pressure increases it increases. While at the focal region the turbulent intensity remains constant.

On increasing jet diameter ratio, skin friction coefficient decreases linearly. Moreover, on increasing operating pressure the rate of decline in skin friction is more significant for lower operating pressure.

It has found that with increasing jet diameter ratio the velocity linearly increases. However, also on increasing operating pressure the velocity increases.

Increasing the jet diameter ratio the pressure significantly decreases. This is because of increase in area leads to decrease in pressure. Therefore, pressure magnitude decreases less radically as operating pressure increases.

The turbulent intensity across the axis decreases significantly as jet diameter ratio increases and get constant when at higher at jet diameter ratio. While, the outlet the turbulent intensity continuously goes on decreasing.

REFERENCES

[1] E. Siores, W. C. K. Wong, L. Chen, J. G. Wager, "Enhancing Abrasive Waterjet Cutting of Ceramics by Head Oscillation Techniques", CIRP Annals - Manufacturing Technology Volume 45, Issue 1, 1996, Pages 327–330

[2] A. E1-Domiaty I and A. A. Abdel-Rahman, "Fracture Mechanics-Based Model of Abrasive Waterjet Cutting for Brittle Materials", Int J Adv Manuf Technol (1997) 13:172-181

[3] A.I Hassan and J. kosmol, "Dynamic elastic-plastic analysis of 3D deformation in abrasive water jet machining", journal of material processing technology 113 (2001) 337-341

[4] J. Wang, D.M. Guo, "A predictive depth of penetration model for abrasive waterjet cutting of polymer matrix composites", Journal of Materials Processing Technology 121 (2002) 390–394

[5] F.L chen and E. siories, "The effect of cutting jet variation on surface striation formation in abrasive water jet cutting", journal of material processing technology 135(2003) 1-5

[6] H. Liu , J. Wang, N. Kelson , R.J. Brown, "A study of abrasive waterjet characteristics by CFD simulation", Journal of Materials Processing Technology 153–154 (2004) 488–493

[7] GuihuaHu, Wenhua Zhu, Tao Yu and Jin Yuan, "Numerical Simulation and Experimental Study of Liquid-solid Two-phase Flow in Nozzle of DIA Jet", IEEE international conference korea (2008)

[8] Guihua Hu, Wenhua Zhu, Tao Yu, and Jin Yuan, "Numerical Simulation and Experimental Study of Liquid-Solid Two-Phase Flow in Nozzle of DIA Jet", ICIC 2008, CCIS 15, pp. 92–100, 2008. © Springer-Verlag Berlin Heidelberg 2008

[9] D.A. Axinte , D.S. Srinivasu , J. Billingham, M. Cooper, "Geometrical modelling of abrasive waterjet footprints: A study for 908 jet impact angle", CIRP Annals - Manufacturing Technology 59 (2010) 341–346

[10] NIE Baisheng , WANG Hui, LI Lei, ZHANG Jufeng, YANG Hua, LIU Zhen, WANG Longkang, Li Hailong, "Numerical investigation of the flow field inside and outside high-pressure abrasive waterjet nozzle", Procedia Engineering 26 (2011) 48 – 55

[11] UHLÁŘ Radim, HLAVÁČ Libor, GEMBALOVÁ Lucie, JONŠTA Petr,and ZUCHNICKÝ Ondřej, "Abrasive Water Jet Cutting of the Steels Samples Cooled by Liquid Nitrogen", Applied Mechanics and Materials Vol. 308 (2013) pp 7-12

[12] Adnan Akkurt, "The effect of cutting process on surface microstructure and hardness of pure and Al 6061 aluminium alloy", Engineering Science and Technology, an International Journal xxx (2014) 1e6

[13] Yong Wang, Hongtao Zhu, Chuanzhen Huang, Jun Wang, Peng Yao, Zhongwei Zhang, "A Study on Erosion of Alumina Wafer in Abrasive Water Jet Machining", Advanced Materials Research Vol. 1017 (2014) pp 228-233

[14] Fang-Jung Shiou∗, Assefa Asmare, "Parameters optimization on surface roughness improvement ofZerodur optical glass using an innovative rotary abrasive fluidmulti-jet polishing process ",Precision Engineering xxx (2015) xxx–xxx