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Analysis of Two-Phase Flow with respect to Nozzle Angle in Abrasive Jet Machining Using CFD

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ABSTRACT: *Abrasive Jet Machining (AJM) is a non-traditional machining process that utilizes a high-velocity mixture of gas and abrasive particles to remove material from a workpiece. The nozzle angle plays a critical role in determining cutting efficiency, material removal rate (MRR), and surface finish. This study investigates the effects of nozzle angle on two-phase flow characteristics in AJM using Computational Fluid Dynamics (CFD) simulations. The research involves modeling and simulating the fluid-particle interaction within the jet stream, analyzing parameters such as velocity distribution, particle trajectories, pressure variations, and impact forces at different nozzle angles (30°, 45°, 60°, and 90°). The CFD results are validated through experimental data to evaluate the optimal nozzle orientation for maximum machining efficiency. The findings provide insights into how nozzle angle influences particle dispersion, impact energy, and erosion patterns, leading to improved machining precision and reduced abrasive consumption. This research contributes to the optimization of AJM processes, making them more efficient and cost-effective for industrial applications such as micromachining, glass cutting, and surface finishing.*

Keywords: *Abrasive; Machining; CFD; Nozzle; Process parameters*

I. INTRODUCTION

An abrasive fluid jet machining (AFJM) is one of the most recently developed non-traditional manufacturing processes as this process is being widely used for machining of hard to machine materials like ceramics, ceramic composites, fiber-reinforced composites, and titanium alloys where conventional machining is often not technically or economically feasible. Usually, the water exits a nozzle at a very high speed and the abrasive material is injected into the jet stream. This process is sometimes known as entrainment in which the abrasive particles become part of the moving water. The purpose of the abrasive fluid jet machining (AFJM) is to perform some machining or finishing operations. The use of the AFJM for machining or finishing purposes is based on the principle of erosion of the material upon which the jet hits. It is the primary purpose of the jet to deliver the abrasive material to the work piece for the purpose of erosion; thereby the desired shape of the material is obtained. Liu et al [1] has done experiments on AFJM and they have suggested that cutting performance has been completely independent of standoff distance and they have also shown that the velocity and pressure variation in the radial direction is not significant within about 80% to 90% of the jet diameter. Kramar et al [2] have studied the effect of the input variables in AFJM such as generated sound, vibrations of the work piece and the back flow pressure of the jet and they proved that through semi empirical modeling, it was possible to increase the machining quality and reduce the machining cost and time simultaneously. Deepak et al [3] have concluded that the increase in inlet pressure of the abrasive particles results in induced wall shear stress, which leads to increase in the kinetic energy of the abrasive particles. Ray et al [4] have done experiments on AFJM to optimize material removal rate (MRR) by varying the parameters such as air pressure, grain size of the material and nozzle diameter and they have concluded that MRR increases with increase of air pressure and starts to decrease when the pressure reaches a threshold value and they have also reported that the MRR increases with increase in grain size and the nozzle diameter. Bhaskar et al (5) have done experiments on AFJM by altering the process parameters to obtain enhanced MRR and they have observed that when the nozzle tip distance increases, the top surface diameter and bottom surface diameter of the hole increases and they also noted the increase in MRR when the pressure increases. Lebar et al [6] have done simulations on physical modeling of AFJM and compared the results with the practical setup and made measurable analysis in the impact of abrasive grain. Coray et al [7] have extended the current knowledge of abrasive water jets by determining the kinetic energy distribution of the abrasive particles and the structure of the jet in dependence of the cutting head parameters. Dewan et al (8) have developed a CFD method to find out the particle, water and air velocity distributions for AFJM by using a multi-phase approach and they have concluded that the jet velocity depends on the acceleration process of water and abrasive particles and have performed the simulation using different taper inlet angles and they have reported that the acceleration process of the abrasive particles was much better for higher taper inlet angle leading to the maximum velocity of the jet at the exit of the focus tube. Jurisevic et al [9] have performed experiments on AFJM by varying the parameters such as vibrations of the work piece, the generated sound, back pressure of the jet and have improved the machining accuracy as well as the output parameters. Kovacevic et al

(10) have predicted and compared the velocities and trajectories of the solid particles by conducting CFD analysis for the steady state, turbulent, solid–liquid flow through nozzles used in premixed abrasive water jet cutting systems.

OBJECTIVE

- To analyze the flow characteristics of abrasive water jet on the inside surface of thenozzle
- To analyze the effect of shear properties on the surface of nozzle with Water jet
- To optimize nozzle dimensions and process parameters to minimize the nozzle wearusing taper angle of nozzle, inlet pressure of water jet, energy dissipation.

II. CFD ANALYSIS

Modeling

Modeling was done using Pro E Wild Fire 2.0 and exported in IGES format. The models of nozzle heads have been shown in figure 1 with a taper angle of 45°. The parameters have been kept constant for the machining, such as focus tube diameter as 0.76 mm, focus tube length as 76mm, taper angle of the nozzle as 45°, mixing chamber diameter as 6mm, mixing chamber length as 12mm, orifice diameter as 0.2mm, water inlet diameter as 2.5mm and abrasive inlet diameter as 3mm. The modeling of nozzle with taper angle of 45° and 60° and mixing chamber has been shown in figure 1. Similar models have also been created for the taper angles of 15° and 30°.

Figure 1 Modeling of Nozzle with taper angle of 45° and 60°

Meshing

Meshed file of taper angle 45° and 60° has been shown in figure 2 (a) and (b). After model meshing, the grids on model have to be optimized. This step has been essential as it helps in minimizing the numerical errors in computation during the simulation work. In order to determine the intention of the optimization process, an acceptable grid size that can reach a balance between the amount of computing time and the accuracy in the solution of flow variables.

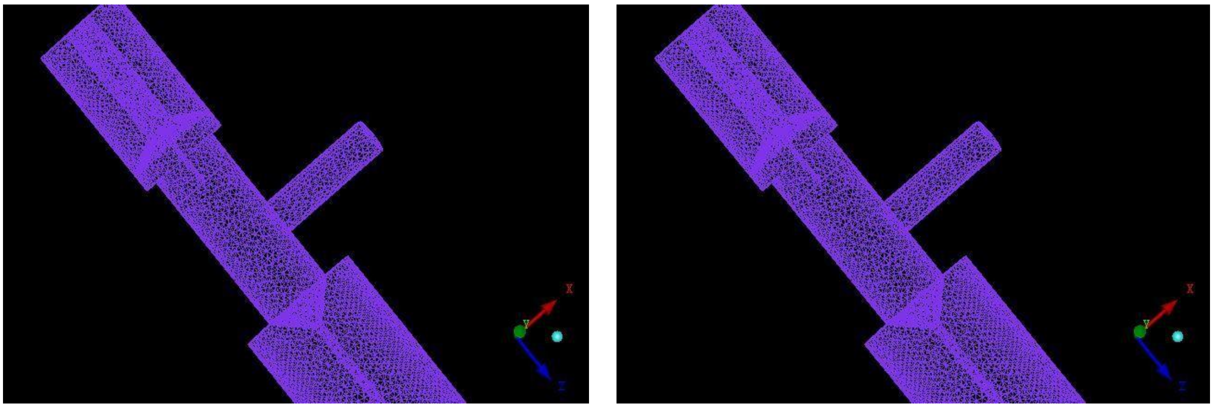

Figure 2 (a) and (b). Taper angle of the nozzle with 45° and 60°

Process Parameters

After meshing, the following process parameters and domains have been illustrated for further analysis.

Water Inlet Pressure P_i – 400 bar

Density of water ρ_w – 1000 kg/m^3

Velocity of water $V_w = \sqrt{\frac{2P_i}{\rho_w}}$

$= \sqrt{\frac{2*400x10^5}{1000}}$

$= 282.84$ m/s

Mass flow rate of water $m_w = \rho_w * Q_w$

Volume flow rate of water $Q_w = \frac{\pi}{4} * d^2 * V_w$

Diameter of orifice $d = 0.2$ mm

$m_w = 1000 * \frac{\pi}{4} * (0.2x10^{-3})^2 * 282.84$

$m_w = 0.533$ kg/min

Velocity of abrasive water jet $V_{awj} = \frac{1}{1+\frac{m_{abr}}{m_w}} * V_W$

Mass flow rate of abrasive $m_{abr} = 0.45$ kg/min

$= \frac{1}{1+\frac{0.45}{0.533}} * 282.84$

$V_{awj} = 153.36$ m/sec

Preprocessing

The meshed model is exported in .msh format and is used in CFX tool. The CFD analysis was executed with following domain specifications and boundary conditions. The figure 3 shows the domains modeled using CFD.

Solver Stage

After defining all the conditions the model has been imported in CFX- Solver Module in .def format for doing iterative calculations and to generate the result file. The solver control parameters have been specified in CFX-Pre Module, such as number of iterations as 100 withauto time scale control and a residual target of 1e-4.

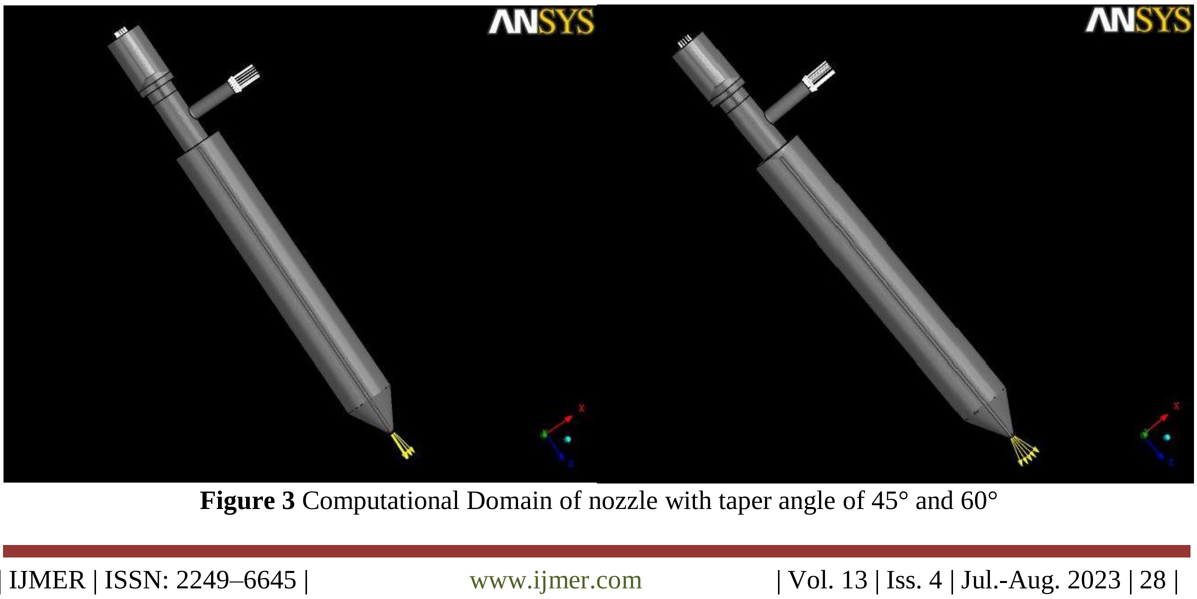

Figure 3 Computational Domain of nozzle with taper angle of 45° and 60°

III. RESULTS AND DISCUSSION

Velocity Variation

The velocity variation along the mixing chamber and focus tube length has been shown in figure 4 (a) and (b). In the case of mixing chamber the velocity reduces gradually and increases when it reaches near the end of tube. In the case of focus tube, the gain in velocity is observed when the flow past the nozzle. Further kinetic energy lost has been observed when the flow was along the focus tube for all the cases. This may be due to some of the abrasive particles may collide with the focusing tube wall. Hence, there has been some overall velocity reduction as the jet exits the focusing tube. The kinetic energy lost has been high in the cases of taper angle 30° and 60° and it has been significantly less in the case of 45° taper angle.

Wall shear distribution

The wall shear stress distribution along the mixing and focus tube length has been shown in figure 5 (a) and (b). Figure 5 (a) shows that increased wall shear at the entry of mixing chamber for 60° taper angle. The magnitude decreases till the mixing region after that it increases sharply along its flow. Figure 5 (b) shows that the wall shear increases when the tape angle increases. Increased magnitude of wall shear has been observed for 60° taper angle.

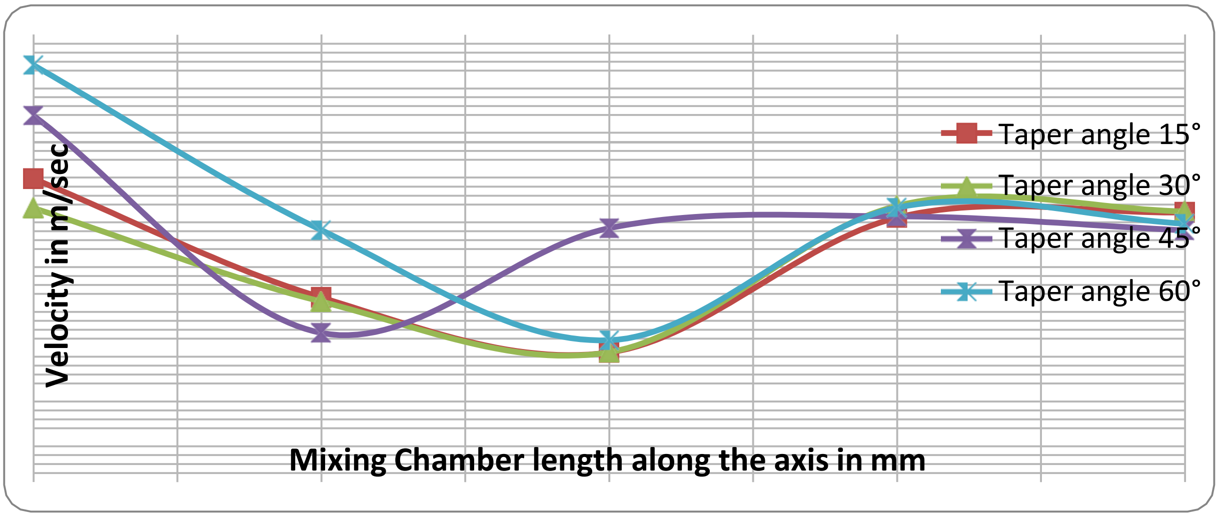

Figure 4 (a) Velocity variation along the Mixing Chamber

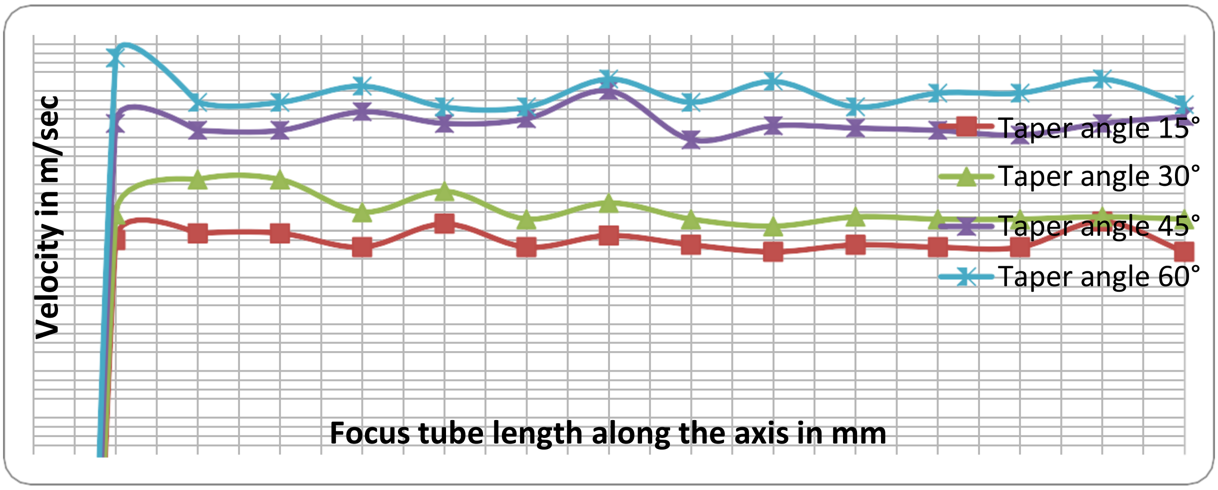

Figure 4 (b) Velocity variation along the Focus tube

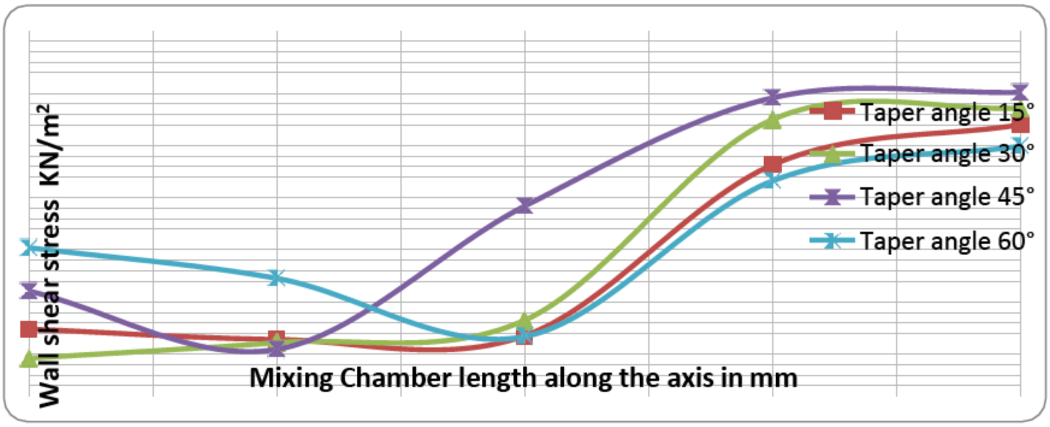

Figure 5 (a) Wall shear stress in mixing chamber

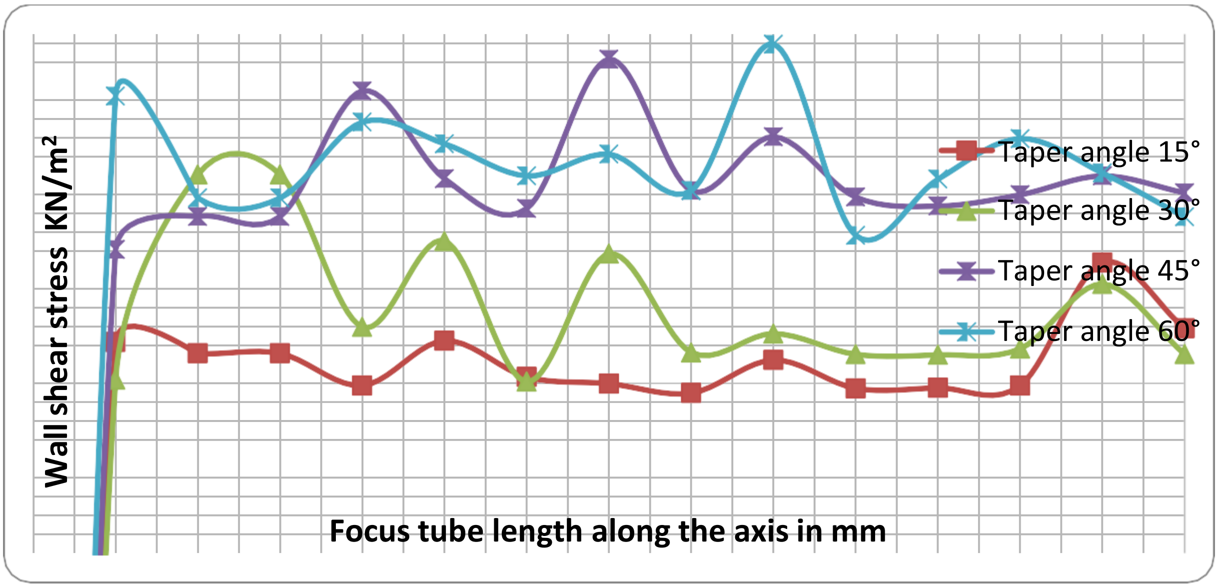

Figure 5 (b) Wall shear stress along focus tube

Pressure Gradient

The pressure gradient along the mixing and focus tube length has been shown in figure 6 (a) and (b). The pressure gradient in the flow causes the axial velocity to decrease and cause for eddies which will consequently increase the energy dissipation. Figure 6(a) that the pressure gradient decreases sharply towards the mixing region and it increases gradually towards outlet of Mixing Chamber. It has been observed from the same figure that the pressure gradient is comparatively very high at the entry and exit of mixing chamber for the 30° taper angle. Figure 6 (b) shows that increased pressure gradient along the focus tube. It has also been observed from figure 6 (b) that the pressure gradient has been relatively low for 45° taper angle.

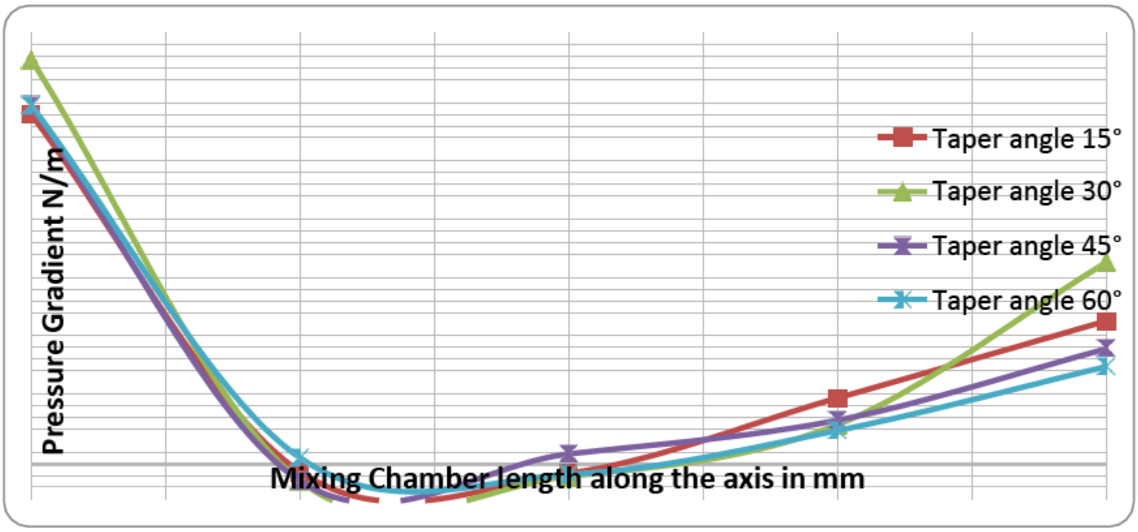

Figure 6 (a) Pressure gradient in the mixing chamber

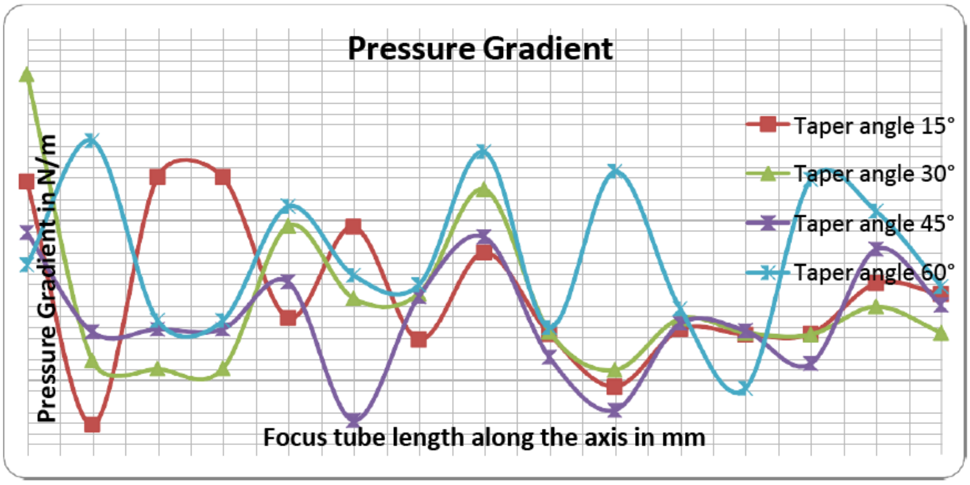

Figure 6 (b) Pressure gradient in the focus tube

IV. CONCLUSION

Thus CFD analysis of flow through nozzle of abrasive fluid jet machining has been carried out and the following conclusion has been drawn.

- Loss in kinetic energy has been observed when the flow is along the focus tube. This may be due to some of the abrasive particles do collide with the focusing tube wall. The kinetic energy loss is relatively less for 45° taper angle
- The magnitude of wall shear stress increases when the taper angle increases. The wall shear in the mixing chamber increases sharply after the mixing region.
- The energy dissipation due to wall shear is relatively low for 30° taper angle.
- The pressure gradient is comparatively less for 45° taper angle.

At the whole, taper angle with 45° seems to be an optimal solution in nozzle design.

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