PRESSURE-VELOCITY CHARACTERISTICS STUDY OF CUTTING FLUID FLOWING THROUGH A SUDDEN CONTRACTION CONFIGURATION

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Abstract: The delivery of cutting fluid plays an important role in any machining operation. Cutting fluid is generally delivered to the cutting zone through nozzle. The shape of the nozzle influences the fluid velocity, pressure and flow characteristics at its exit. By increasing the velocity of cutting fluid the heat generated in metal cutting operation can be reduced quickly. The nozzles generally used for delivery of cutting fluid are gradually converging type. But in a gradually converging nozzle the length becomes high for a low convergence angle. Sudden contraction configuration of the fluid delivery nozzle can be tried where the same velocity is expected to be achieved with a shorter length of the nozzle. In this work the effect of Re on $P_{centerline}$ and $V_{centerline}$ have been investigated for a sudden contraction configuration of having contraction ratio of 2. Here Re has been taken with a range between 50 to 500. It is observed that $V_{centerline}$ increases along the length but $P_{centerline}$ decreases along the length at a particular value of Re. At any location, the $P_{centerline}$ and $V_{centerline}$ increases with the increase in Re.

Keywords: Contraction ratio, convergence angle and sudden contraction.

Introduction: A nozzle is a converging section of fluid carrying duct where the velocity of the flow increases by decreasing the pressure. One of the most important applications of nozzle is to deliver cutting fluid in metal cutting operations. For delivery of cutting fluid generally we use gradual converging nozzle with less converging angle. If we use sudden converging nozzle instead of gradual converging nozzle then same velocity can be achieved with a shorter length. The flow characteristics are found to be a function of geometrical parameters of the flow passage characterized by contraction ratio (CR) and the flow parameters are represented by the Reynolds number (Re).

From the literature review, it has been observed that a number of authors have worked on sudden contraction nozzle. But unfortunately no literature has yet been found that the application of sudden converging nozzle in metal cutting operation. **Irani *et al*** [1] have studied some of the common cutting fluid delivery system that has been employed in recent years. They have found that the jet nozzle appears to most effective for industry. **Li** [2] has numerically analyzed the relationship between the heat transfer coefficient and jet flow rate. He has found that the heat transfer rate increases with increase in jet flow rate. **Hammad *et al.*** [3] have numerically studied the flow characteristics through axisymmetric sudden contractions nozzle using computational fluid dynamics tools. They have introduced a new nozzle with sudden contraction that optimizes the characteristics of the jet. **Webster *et al.*** [4] have proposed a coherent jet nozzle which is most suitable for grinding operations. They have presented a new nozzle design that gives a long coherent jet up to 45 m/s to maximize the application of fluid in grinding zone. They have found a 26.5% increase in wheel life as a result of coolant application optimization during grinding of an aerospace component.

Mathematical formulation

Computational Domain: Schematic diagram of the computational domain for flow through sudden contraction configuration is illustrated below. It is assumed that the flow under consideration is steady, two-dimensional, laminar and axisymmetric and the fluid is incompressible and Newtonian.

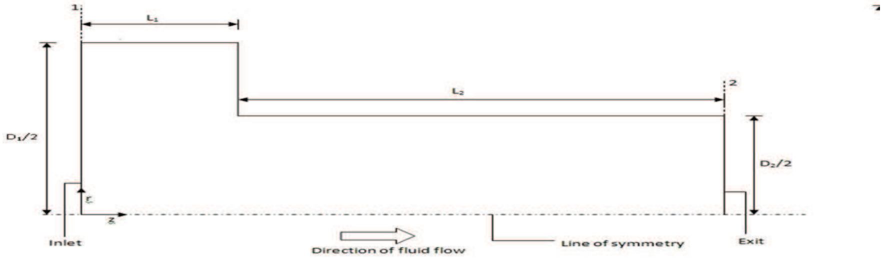


Fig2.1: Schematic diagram of the computational domain of flow through an axisymmetric sudden converging nozzle

Governing Equations: For getting the governing equation following dimensionless variable are to be defined. Lengths: $r^* = r/D_1$, $z^* = z/D_1$, $L_1^* = L_1/D_1$, $L_2^* = L_2/D_1$.

Velocities: $u_r^* = u_r/U$, $u_z^* = u_z/U$.

Pressure: $p^* = p/\rho U^2$.

By the help of above dimensionless variables the continuity equation and Navier-Stokes equations in two-dimensional cylindrical coordinates (r,z) can be written in the differential form as follows:

Continuity equation:

$$\frac{\partial}{r^* \partial r^*}(r^* u_r^*) + \frac{\partial}{\partial z^*}(u_z^*) = 0 \quad (1)$$

r-direction momentum equation:

$$\frac{\partial (r^* u_r^* u_r^*)}{r^* \partial r^*} + \frac{\partial (u_z^* u_r^*)}{\partial z^*} = -\frac{\partial p^*}{\partial r^*} + \frac{1}{\mathrm{Re}}\left(\frac{\partial}{\partial r^*}\left(\frac{\partial (r^* u_r^*)}{r^* \partial r^*}\right) + \frac{\partial^2 u_r^*}{\partial z^{*2}}\right) \quad (2)$$

z-direction momentum equation:

$$\frac{\partial (r^* u_r^* u_z^*)}{r^* \partial r^*} + \frac{\partial (u_z^* u_z^*)}{\partial z^*} = -\frac{\partial p^*}{\partial z^*} + \frac{1}{\mathrm{Re}}\left(\frac{\partial}{r^* \partial r^*}\left(r^* \frac{\partial u_z^*}{\partial r^*}\right) + \frac{\partial^2 u_z^*}{\partial z^{*2}}\right)$$

(3)

Where, the flow Reynolds number, $\mathrm{Re} = \rho U D/\mu$.

Boundary Conditions: For the present problem four different type of boundary condition has been taken. They are as follows,

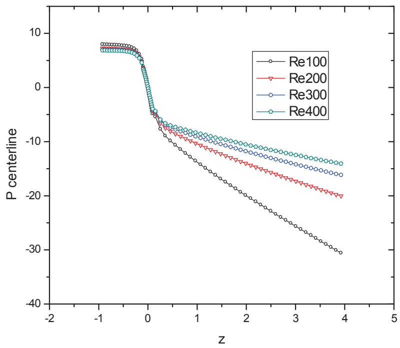
1. At the walls: there is no slip condition, i.e., $u_r^* = 0$, $u_z^* = 0$.
2. At the inlet: Axial velocity will be specified and the transverse velocity will be set to zero, i.e., $u_z^* = specified$, $u_r^* = 0$. Inlet is specified as fully developed flow condition, i.e., $u_z^* = 2.0\left[1 - (2r^*)^2\right]$.
3. At the exit: Constant pressure boundary has been adopted.
4. At the line of symmetry: The normal gradient of the axial velocity and the transverse velocity will be set to zero, i.e., $\partial u_r^*/\partial z^* = 0$, $u_r^* = 0$.

Numerical Procedure: The governing equations have been solved numerically by the CFD code, which is developed using integral approach of the finite volume method on a non-uniform staggered grid following SIMPLER algorithm (**Patankar [5]**). The discretized equations have been solved using Tri-diagonal Matrix Algorithm (TDMA) with Alternate Direction Implicit (ADI) scheme. When the normalized residuals for momentum and mass equations summed over the entire calculation domain falls below 10^{-8} then the convergence of the iterative scheme has been considered to be achieved. In this present work, the inlet diameter has been taken as 1 and the outlet diameter as 0.5. The non-dimensional length of the computational domain has been chosen to be 5 in which the inlet length is 1 and outlet length is 4. During computations, the numerical mesh comprises of 57×41 grid nodes in the inlet section and 96×21 in exit section in r and z directions respectively.

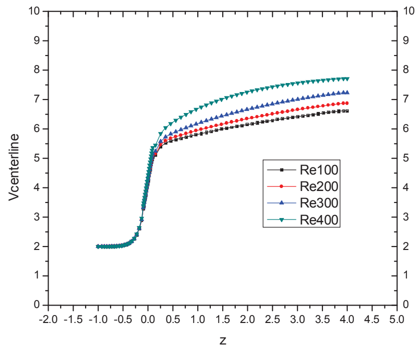
Results and Discussion: In this work the effect of Re on $P_{centerline}$ and $V_{centerline}$ have been investigated. The Reynolds number has been varied from 50 to 500 and the inlet velocity has been considered to be fully developed. In this study, the contraction ratio has been defined as the ratio of diameter of the inlet to sudden contraction section diameter. A fixed contraction ratio of 2 has been taken into consideration for this numerical work.

Variation of centerline pressure and centerline velocity: Fig 3.1 (A) & (B) shows the variation of $P_{centerline}$ and $V_{centerline}$ for four different Re ranging between 50 to 500 and the contraction ratio is fixed as 2. From the figure it is observed that the $P_{centerline}$ decreases steadily after the throat region and the $V_{centerline}$ increases steadily after the throat. It is also noticed that both $P_{centerline}$ and $V_{centerline}$ increases with the Re.

Conclusion: In the present numerical study, flow characteristic through sudden contraction has been carried out and the effect of important parameters like Reynolds number(Re) has been investigated. The Pcenterline decreases along the length. That means the velocity at the exit of the nozzle will be high which will tends to increase the heat transfer rate of the cutting fluid. The $V_{centerline}$ increases steadily after the throat region and at the exit of the nozzle the velocity of the flow will be high, by which the heat transfer rate will increase.



(A)



(B)

Figs 3.1 centerline pressure & centerline velocity for different Reynolds number

Nomenclature :

Symbol	Meaning	Units
D_1, D_2	Inlet and exit diameter	M
L_1, L_2	Inlet length and exit length	M
Re	Reynolds number	–
U	Average velocity	ms^{-1}
u_z, u_r	Velocity in z-direction and r-direction	ms^{-1}
z, r	Cylindrical co-ordinates	–
ρ	Density	kg m^{-3}
μ	Dynamic viscosity	kg $m^{-1}s^{-1}$
$P_{centerline}$	Centerline pressure	N/m^2
$V_{centerine}$	Centerline velocity	m/s

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