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LAMINAR MODELING AND SIMULATION ON CUTTING FLUID FLOW THROUGH SUDDEN CONTRACTION NOZZLE

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Abstract— In this paper an attempt has been made to study the flow characteristics of a cutting fluid flowing through a sudden contraction nozzle. In present work an extensive numerical study on the performance of a cutting fluid flow through a sudden converging nozzle has been done. The Nevier-Stokes equation, continuity equation and energy equation are solved by using finite volume base upwind scheme for different Reynolds Numbers and for a fixed aspect ratio. Computations have been done with respect to wall static pressure, wall shear stress and stream line contours for sudden contraction configuration contraction ratios 0.28 have been taken. Computation have been done on the wall static pressure (WSP), Wall shear stress (WSS) and total temperature and their variation for sudden contraction also have been found out. The numerical result has been shown in details in result and discussion sections by using ANSYS FLUENT.

Keywords— Streamline contours, centerline velocity, wall shear stress, wall static pressure, contraction ratio, laminar flow, total temperature.

INTRODUCTION

The Cutting fluid is one of the important aids to improve production efficiency. In a modern workshop practice or any industry using power, an enormous amount of power is lost either by the generation of heat or by friction between tool surface and work piece. Heat in the cutting process is generated by plastic deformation and by chip or tool friction at the rake and flank faces. It has been seen that the amount of power lost due to generation of heat varies from 20-30 percent and hence to reduce it, the use of cutting fluids came into existence in the field of production technology. Cutting forces can also be considerably reduced by using suitable cutting lubricants when machining metals at speeds bellow 0.7m/sec.

List of symbols:

Re	Reynolds number
u	Velocity in z-direction (ms^{-1})
v	Velocity in r-direction (ms^{-1})
x, y	Cartesian co-ordinates
ρ	Density ($Kg\ m^{-3}$)
μ	Dynamic viscosity ($Kg\ m^{-1}s^{-1}$)
SC	Sudden Contraction
CR	Contraction Ratio
Wi	Width at inlet of computational domain (m)
Wx	Width at exit of computational domain (m)
Li	Inlet length of computational domain (m)
Lx	Exit length of computational domain (m)

A cutting fluid must contribute in three ways to a machining process. First, it must act as a lubricant. By reducing friction, it reduces the heat generated. Second frictional heating cannot be completely eliminated and often, not even substantially reduced. The cutting fluid must also act as an effective coolant. Third finally, It should act as an anti-weld agent to counteract the tendency of the work material to weld the tool under heat and pressure. For an effective machining operation the cutting fluid must have the following desirable properties .High thermal conductivity to carry away the generated heat. Good lubricating qualities to produce low co-efficient of friction .High flash point as to eliminate the hazard of fire. It should protect the machined surface from oxidation. Must not promote gummy or solid participate at ordinary working temperature. Must not promote corrosion to the tool, work or the machine . Must not cause skin irritation or contamination .Should be odorless even after long use .Neutral so as not to react chemically. On-corrosive to the tool , work of the machine. Transparency so that the cutting action of the tool may be observed. Low viscosity to permit free flow of the liquid. Low priced to minimize production cost. During the review of literature, initially review is carried on the need of cutting fluid in metal cutting operation. It is found that a number of authors have published paper regarding the need of cutting fluid in metal cutting operation. Some of them have focused on the velocity and pressure at the exit of the nozzle .In all the cases they have used gradually converging nozzle for achieving the required velocity and pressure. I found one paper Raises etal. who have done an experiment by taking a sudden contraction nozzle. They concluded that a sudden contraction nozzle creates a relatively small recirculation bubble immediately downstream of the nozzle contraction. Chakrabarti et al. discuss how the finite volume method is s used for volume discretization in low Reynolds Number fluid flow in sudden expansion. Baines-Jones et al. elaborated in his discussion that the coherent jet appears to be the most effective for industry at the present time . Kishawyet al. described the results of application of different coolant strategies to High speed milling of aluminum alloy A356 for automotive industry. They have investigated the effect of flood coolant, dry cutting and minimum quantity of lubricant (MQL) technologies on tool wear, surface roughness and cutting forces. AISialloy.Iraniet al. have studied some of the common cutting fluid delivery system that has been employed in recent years. That have found that the jet nozzle appears to most effective for industry, where as shoe nozzle and radial jet systems have the capacity to change cutting fluid application. Jacksonet al. have described how computational techniques have been used to develop ax-symmetric, straight, sonic-line, minimum length micro nozzles for laser micro-machining applications. Diniz and Micaroni have described haw tool wear mechanisms are influenced by fluid pressure, flow rate and direction of application in finish turning of AISI 1045 steel using coated carbide tools. Raiseeet al. have experimented and found that a sudden contraction creates a relatively small recirculation bubble immediately downstream of the nozzle contraction. This separation bubble influences the distribution of local heat transfer coefficient and can increase the heat transfer levels by a factor of three. Promvonge and Eiamsa-ard have described the experimental study of the influence of Conical-nozzle turbulator inserts on heat transfer and friction characteristics in a circular tube. In their work, the turbulators are placed in the test tube section with two different types : (1) Diverging nozzle arrangement (D-nozzle turbulator) and (2) converging nozzle arrangement (C- nozzle turbulator. Morganet al. have presented a new analytical model to predict the coherent length of the nozzle. Their work presents new insight into the internal nozzle flows and the coherent length of a wide range of nozzle design .Shujaet al. have considered annular nozzle and jet impingement on to a conical cavity, and examined heat transfer rates from the cavity surfaces for various jet velocities, two outer angles of annular nozzle, and two cavity depths. They have taken a numerical scheme with the control volume approach to simulate the flow situation and predict the heat transfer rates. They have found that increasing jet velocity at the nozzle exit modifies the flow structure in the cavity while altering the heat transfer rates and skin friction,; in which case, increasing nozzle outer angle and jet velocity enhance the heat transfer rates .Balakrishnaet al. [2010] have studied the change of flow patterns during the simultaneous flow of high viscous oil and water through the sudden contraction and expansion in a horizontal conduit. They have observed that these sudden changes in cross-section have a significant influence on the downstream phase distribution of lube oil-water flow. .Chakrabartiet al. has discussed the performance of a sudden expansion with fence. He has considered the Reynolds number ranges from 20 to 200. His computations revealed that for high Reynolds Number the use of a fence always increases effectiveness of diffusion process compared to simple sudden expansion configuration. Alkberdiet al. threw some lights on the research works devoted to the optimization of usable flow rate in grinding operations. However, there is still some field of work dealing with the analysis of nozzle geometry, and its influence on jet pressure distribution. From the comprehensive literature review, it has been observed that, none of them have studied the flow characteristics with respect to shape and size of the recirculation bubble, tangential velocity contour, wall static pressure and wall shear stress, so far.

Hence the main aim of this work is to study laminar fluid flow characteristic flowing through a sudden contraction nozzle for different Reynolds number ranging from 100 to 500 for a fixed aspect ratio 0.28 with respect to stream line contour, wall shear stress, wall static pressure and total temperature. The important results have been presented by using ANSYS 13.0 in details in result and discussion section. The major conclusions are reported in the conclusion section.

MATHEMATICAL FORMULATION

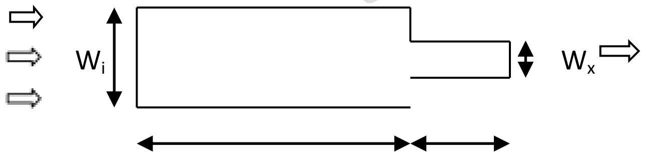

Figure1 Schematic diagram of the computational domain

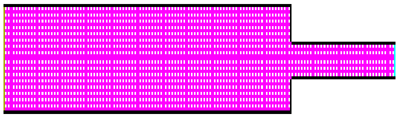

Figure2 Schematic diagram of the computational nodes

GOVERNING EQUATIONS

A. Assumptions

The key line of this work is laminar flow of cutting fluid through a sudden contraction nozzle with considering heat transfer. The flow at the entrance is considered to be uniform and at the exit absolute pressure is assumed. It is assumed that the flow under consideration is steady, two-dimensional, laminar and ax symmetric. Here the fluid has been taken as water which is incompressible and Newtonian. The density of water is taken as (ρ)=998.2 kg/m and dynamic viscosity (μ)= 0.001003 kg/ms.. A schematic diagram of the computational domain is shown in fig1.In this studies the dimensional velocity components and the pressures are governed by the mass momentum and energy conservation equations. For the laminar flow in the nozzle the dimensional governing equation along the x, y directions are as follows:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right) \tag{2}$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right) \tag{3}$$

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)+\mu\left[2\left(\frac{\partial u}{\partial x}\right)^2+2\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial y}\right)^2\right] \tag{4}$$

Where, u is velocity in radial direction, v is the velocity in axial direction, p is pressure, ρ is density, μ is the coefficient of dynamic viscosity.

Boundary Conditions

Three different types of boundary conditions have been applied to the present problem. They are as follows,

(i) At the walls: No slip condition, i.e. u = 0, v = 0.
(ii) At the inlet: Axial velocity has been specified and the transverse velocity has been set to zero, i.e. u = specified, v = 0.
(iii) At the exit: Constant pressure has been specified.

Numerical Procedure

The dimensional partial differential continuity, momentum and energy equations (1)-(4) have been solved according to the SIMPLE method in the finite volume formulation by use of a uniform grid in both coordinating directions. The convection terms have been discretized with the help of upwind scheme. Laminar model has been selected for simulation. In this study for all calculations, the inlet and exit of the nozzle is considered to be 100mm and 36mm respectively, the inlet and exit diameter of the nozzle is considered to be 18mm and 5mm respectively. During computation, the numerical mesh is considered to be comprising of 2312 grid nodes. For this simulation Prandtl number can be considered constant. For this problem the value of μ, ρ and C_p is equal to 0.001003kg/m-s,998.2 kg/m^{3}and 4182 J/Kg K respectively. The convergence of the iterative scheme is achieved when the normal residuals of mass momentum and energy equations summed over the entire calculation domain fall below 10^{-5}.The non-dimensional parameters, which have been considered in this work, are

Reynolds number, Re=$\frac{\rho w u}{\mu}$

Prandtl number, Pr = $\frac{\mu c_p}{k}$

Where k is thermal conductivity (0.6 w/mK) and w is the width of pipe.

Result and Discussion

In this work the effect of Reynolds number on wall static pressure (WSP), wall shear stress (WSS)and streamline contour have been investigated. The parameters during study identified as:

(1) Reynolds number, $100 \leq Re \leq 500$.
(2) Contraction Ratio, CR=0.28

Variation of wall static pressure

The internal pressure generates stresses on pipe which increases with increase in pressure in pipe. When the value of wall stress exceeds the value of working stress of the nozzle material, cracks start initiating and propagating. So, wall static pressure is an important parameter for fluid flow analysis. Figure 1 shows the variation of wall static pressure for five different Reynolds number ranging from 100 to 500 for sudden converging nozzle. In all the cases the wall static pressure decreases along the length of the nozzle. From the figure it has been also observed that in all the cases wall static pressure suddenly decreases to its minimum value at the nozzle throat due to conversion of pressure energy to kinetic energy.

Variation of wall shear stress

Stress distribution in the wall is considered to be important as the wall shear stress may cause the damage to the wall. The alteration in wall shear stress may in lead to further structural changes in the wall of the equipment's. Therefore, the study of the shear stress in the industrial equipment is important. Figure (2) shows the variation of wall static shear stress for five different Reynolds number ranging from 100 to 500. For all the cases wall shear stress decreases along length of nozzle. From the figure it has been also observed that in all the cases wall shear stress suddenly increases to its maximum value at the nozzle throat due to conversion of pressure energy into kinetic energy.

Variation of total temperature

Variations of wall temperature for different Reynolds Number play an important role for flow analysis. Apart from that, temperature distribution in the wall is also considered to be important as it may cause the damage to the wall. Therefore, the study of the wall temperature distributions in the industrial equipment's is important. Figure (3) shows the variation of temperature for five different Reynolds number ranging from 100 to 500 of sudden converging nozzle. From the figure it is also observed that temperature increases with decreasing Reynolds number. From the figure it has been also observed that in all the cases total temperature suddenly decreases to its minimum value at the nozzle throat.

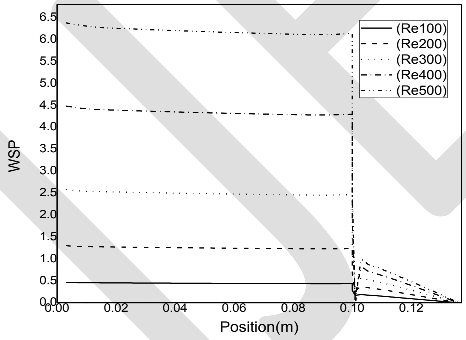

Figure 1 Variation of wall static pressure for different Reynolds number and for a fixed aspect ratio 0.28.

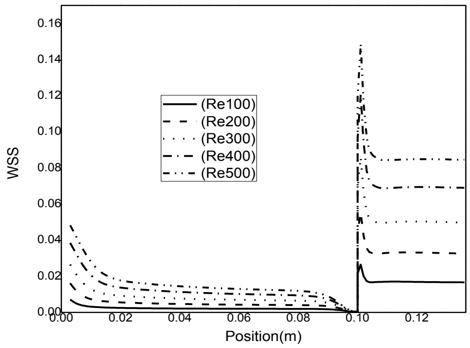

Figure 2 Variation of wall shear stress for different Reynolds number and for a fixed aspect ratio 0.28.

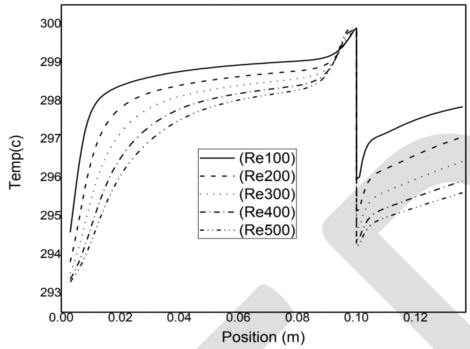

Figure3 Variation of total temperature for different Reynolds number and for a fixed aspect ratio 0.28.

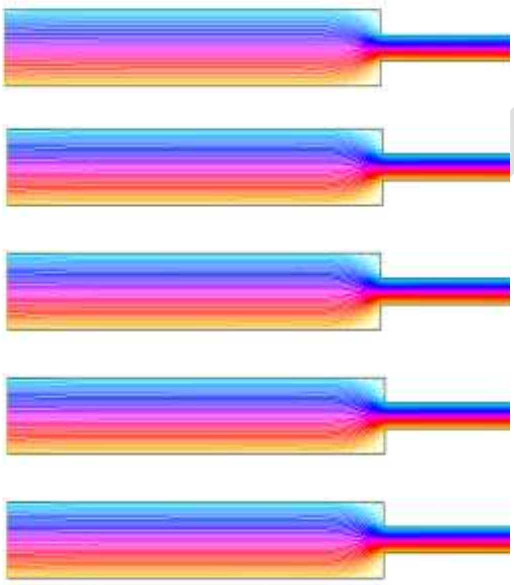

Figure (4) Variation of stream line contours for different Reynolds number and for a fixed aspect ratio 0.28.

STUDY OF STREAMLINE CONTOURS

Streamlines are a family of curves that are instantaneously tangent to the velocity vector of the flow. These show the direction of a fluid element that will travel at any point of time. A description of the various steady laminar flow patterns that may be encountered is, perhaps, best rendered by a display of streamline contour for representative conditions. The streamline contours plots are shown the effect of Reynolds number on the recirculation zone for aspect ratio 0.28. Here five different Reynolds numbers 100, 200, 300, 400 and 500 is considered for aspect ratio shown in figure (4). In all the cases recirculating bubbles has been formed at the throat area due to which rate of heat transfer increases which has been shown in the fig (3).

CONCLUSION

In the present study, the laminar flow characteristics of a water base flowing through a nozzle with considering Reynolds Number ranging from 100 to 500 has been carried out. The effect of Reynolds number on the formation of stream line contour, wall static pressure, wall shear stresses and total temperature have been studied in details. The effect of important parameters likes Reynolds number (Re) and contraction ratio (CR) also has been investigated and this leads to the following conclusions:

1) From the stream line contour, it is revealed that the flow is appreciably affected with the conservancy of nozzle.

2) Wall shear stress gradually decreases along the length of the nozzle from inlet to throat. At the throat of nozzle wall shear stress suddenly increases. After the throat wall shear stress again decreases along the length of the nozzle from throat to exit.

3) The wall static pressure of the sudden contraction nozzle decrease uniformly after the throat. Less pressure on the wall implies more longevity of the nozzle.

4) Total temperature gradually increases from inlet to throat. At the throat the magnitude of wall temperature suddenly increases and becomes maximum , and then suddenly decreases and becomes minimum. Immediately after the throat wall temperature again gradually increases up to the end of the nozzle. It has been also observed that with increasing Reynolds Number wall temperature distribution along the length of the nozzle remain same. Thus, it can be concluded that flow is appreciably affected with increasing Reynolds Number ranging from 100 to 500 for different analysis of Wall static pressure (WSS), Wall shear stress (WSS) and streamline contours. In addition there is another scope of work for similar flow analysis if we carry out the computations for Reynolds Number beyond 500 and vary the Contraction ratio below 0.28 to achieve a nozzle with optimum performance. The numerical work can be carried out with other working fluids; those are used as Cutting fluid in modern industries.3-D model also can be analyzed.

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