DETERMINING THE EFFECT OF NOZZLE GROOVE ON THE 
FLUID FLOW THROUGH VISCOUS 2D PLANAR FLUID

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The study aims to determine the effect of the nozzle groove on fluid flow through the viscous 2D planar fluid. To fulfill the study’s aim, a numerical method was adopted to introduce grooves of different dimensions from the nozzle exit. The study adopts SolidWorks software that was used to design nozzles and introduce groove shaped nozzles, each consisting of six different designs. The nozzle base model used in this study was similar to the one used in a previous study. The procedure was performed with different pressures (8, 10, and 12 bar) at a similar firefighting nozzle. The velocities contours were predicted based on the choice of nozzle section during the numerical stimulation. The present study results demonstrated a new approach that can be used for the increasing velocity at various types of modified nozzles through grooves at different pressures and locations. For grooves, dimensions 1×1 (mm) and location 15 mm at 8 bar, 10 bar and 12 bars showed no effect on velocity as it reduces velocity by increasing surface area. The velocity increases with increasing pressure in the proportion relationship. It clearly explains that the groove does not affect velocity as it rises due to increase in pressure. It is because the groove reduces the velocity by increasing surface area. The study concludes that the use of groove increases the velocity of water that further improves nozzles operation.

Key words: fluid flow, groove, nozzle, CFD

INTRODUCTION

Nozzle device is used for controlling the characteristics and direction of flowing fluid that increases its velocity as it enters or leaves an enclosed pipe or chamber. The nozzle is configured for a bi-directional flow, where pressure decrease in one direction increases the pressure of fluid in the other direction [1]. It is just like a tube or pipe of a definite cross-sectional area used to modify or direct the fluid flow. Therefore, nozzles play an essential role in controlling the flow rate, direction, speed, shape, mass, and pressure of stream emerging from them [2]. The velocity of the fluid within a nozzle increases at the cost of its pressure energy. The primary purpose of the nozzle is to restrict flow that builds up pressure, which is used to project the water stream. One restriction in the form of correct nozzle size is maintaining fluid flow and developing optimum pressure and velocity. For instance, the spray nozzle works at high pressure as the liquid is supplied to a swirl chamber through tangential holes. The liquid in the form of a thin conical sheet is discharged from the nozzle exit orifice and empties into the ligaments [3].

There are various sizes, styles, and shapes of nozzles with a large number of combinations that can be used to encounter the hydraulics problem on the fire ground [4]. The combination of nozzles with different engineer-ing applications is used to generate sprays and jets [5]. They are also widely used as aviation systems, maritime systems, automotive systems, and industrial systems as single equipment or part of equipment [6]. The effect of nozzles on flow characteristics in the spiral nozzle was investigated by Matsuo et al. [7] using an annual slit. The study used velocity distribution downstream of the nozzle exit that was compared with the computational results. Similarly, the flow characteristics of jet expansion pipe nozzles were investigated using the flow visualizations technique [8]. A review was carried out for a free jet from the round pipe installed with a collar at the jet exit. The results demonstrated no difference in jet spreading rate of pipe nozzle with collar and the conventional jet i.e., pipe nozzle without the collar. However, the conventional jet was much smaller than the jet from pipe nozzle with collar. Another study conducted by Alam et al. [9] investigated the impact of flow parameters at nozzle exit by stimulating turbulent flow using Reynolds-averaged Navier-Stokes (RANS) equations via nozzles of different dimensions. The results showed that the dimension of nozzle significantly affected the discharge coefficient. Similarly, Mohamed et al. [10] also studied pressure influence on the flow characteristics using RANS and two transport equations for modelling turbulence. The results showed
that there is a numerical simulation of the compressible flow in a convergent-divergent nozzle. The mechanism of inflow nozzle using direct numerical simulation (DNS) on spatially evolving round jets for the laminar and turbulent jet was investigated by numerous studies [11, 12]. The results showed that it is essential to allow inflow entrainment in the simulation of turbulent jets. Various studies [13, 14] illustrated a shock wave position for various pressure ratios by investigating different shapes of nozzles using the numerical investigation method. The results showed a significant impact of nozzle geometry on the flow structures, including the shock wave location.

The structure of spray and distribution of particle size at nozzle exit was determined by Hespel et al. [15]. The results demonstrated that the atomization process and exit of fluid from the nozzle depend on cavitation. Moreover, the significance of nozzle geometry on subsequent atomization and fluid flow was validated by Agarwal and Trujillo [16], Zhang et al. [17], and Kumar and Sahu [18]. These results may correspond to the study conducted by Satyanarayana et al. [19], showing that fluid properties significantly depend on the cross-section of the nozzle that further affects the flow within the nozzle.

Experiments on two-dimensional nozzles were also performed by Mashida and Sou [20] and Sou et al. [21] for analyzing cavitation in liquid jets under different Reynolds number and cavitation condition. Another study in 1999 was conducted by Badock et al. [22], who focused on the impact of nozzle geometry and internal flow on the velocity of fuel droplets and spray characteristics. However, these studies failed to conclude some promising results. Considering these failures, Hespel et al. [15] aimed to determine particle size distribution and spray structure close to nozzle exit. The results revealed the significant role of cavitation in the process of atomization and exit of liquid and ambient gas from the nozzle. Only a few studies have mainly focused on the numerical simulation of flow within the nozzles.

A recent study by Liao and Deng [23] conducted a numerical simulation of nozzle water jet to analyze exit nozzle diameter, length of the cylindrical section, and convergence angle of the nozzle water jet. The results demonstrated that there is a significant effect of hydraulic cutting on the optimal nozzle parameters. Recently, it is observed that alterations are required in building sizes and elevations in case of fire for maintaining water velocity and flow. Fire can cause loss of lives and monetary loss; therefore, it is essential to manage it with new techniques to prevent hazardous effects. It is believed that more water with increased velocity helps in eliminating obstacles on the way during firefighting. These changes are only possible by generating some new technique. Therefore, there is a need to focus on the effects of nozzle shapes on water flow characteristics in firefighting nozzles with grooves of different dimensions. The present study evaluates the impact of nozzle groove on fluid flow through the viscous 2D planar fluid.

### METHODS

The main stages of study analysis were; pre-processing, simulation, and post-processing. The initial phase of modelling, i.e., the pre-processing step, mainly include; defining geometry, mesh generation, defining boundary conditions, and solver parameters. Constructed models are used at the stimulation stage; whereas, analysis and visualization of the obtained results are conducted at the post-processing stage in the form of contours.

#### Defining nozzle dimensions

The designing of nozzles is done using SolidWorks software that was modified to introduce groove shaped nozzles, each consisting of six different designs (Figure 1). These figures show multiple shapes of grooves with different dimensions and locations. The dimensions and distance of grooves from the nozzle exit are illustrated in Table 1.

| Type of groove | Dimension (mm) | Distance from exit (mm) |
|----------------|----------------|------------------------|
| A              | 1x1            | 10                     |
| B              | 1x1            | 15                     |
| C              | 2x2            | 10                     |
| D              | 2x2            | 15                     |
| E              | 1x1            | 7 and 15               |
| F              | 2x2            | 7 and 15               |

The nozzle base model used in this study is similar to the one used by Zhang et al. [24]. All the nozzles presented in this study had these dimensions; 141.96 mm in length, 50 mm in diameter at the inlet, and 20 mm diameter at the outlet. The flow field considered in this case is steady, incompressible, and possess turbulent isothermal flow, with tensor form as follows in equation (1):

\[ \frac{\partial p}{\partial x_j} = 0 \]  

Equation 2 shows the formula to calculate the equation of incompressible viscous fluid motion:

\[ \frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} (u_i u_j) = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j^2} \]  

The different geometries of nozzles set in ANSYS FLUENT– Design Modeler platform specify the physical boundaries of the fluid. The present study selected type 2D, and each dimension for every nozzle were defined according to the model. The nozzle models for grooves are shown in Figure 2; whereas, the geometries are illustrated in Table 2.

#### Meshing and Boundary

The nozzle structure is axisymmetric, which comprises...
Figure 1: Groove designs; (a) dimension 1x1 at 10; (b) dimension 1x1 at 15; (c) dimension 2x2 at 10; (d) dimension 1x1 at 15; (e) dimension 1x1 at 7 and 15; (f) dimension 2x2 at 7 and 15 (all unit in mm)

Figure 2: Groove models; (a) dimension 1x1 at 10; (b) dimension 1x1 at 15; (c) dimension 2x2 at 10; (d) dimension 1x1 at 15; (e) dimension 1x1 at 7 and 15; (f) dimension 2x2 at 7 and 15 (all unit in mm)
Table 2: Geometry of groove models

| Nozzle Model type (Grooves) | Geometries parameters |
|-----------------------------|------------------------|
| Model 2a                    | One groove with dimensions of $1\times1$ mm and distance from nozzle exit 10 mm. |
| Model 2b                    | One groove with dimensions of $1\times1$ mm and distance from nozzle exit 15 mm. |
| Model 1c                    | One groove with dimensions of $2\times2$ mm and distance from nozzle exit 10 mm. |
| Model 2d                    | One groove with dimensions of $2\times2$ mm and distance from nozzle exit 15 mm. |
| Model 2e                    | Double grooves with dimensions of $1\times1$ mm, 7mm distance for first ring and 15mm for second ring from nozzle exit. |
| Model 2f                    | Double grooves with dimensions of $2\times2$ mm, 7mm distance for first ring and 15 mm for second ring from nozzle exit. |

Table 3: Mesh type and number of nodes

| Mesh       | Coarse   | Medium   | Fine     |
|------------|----------|----------|----------|
| Number of nodes | 8,00,000 | 1,200,000 | 1,400,000 |

Figure 3: Flow rate for different mesh number

Figure 4: Axial velocity component (current study Vs. Zhang et al. [24])

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{flow_rate.png}
\caption{Flow rate for different mesh number}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{axial_velocity.png}
\caption{Axial velocity component (current study Vs. Zhang et al. [24])}
\end{figure}

Analysis

The nozzles were designed using SolidWorks software; while, ANSYS FLUENT 15.0 that is a computational fluid dynamics software package was used for stimulating the incompressible and viscous planar fluid across the nozzles. ANSYS ICEM was used for mesh generation and ANSYS FLUENT for flow analysis.
RESULTS AND DISCUSSION

The effect of groove dimensions $1\times1$ (mm) and location 10 mm at 8 bar, 10 bar and 12 bars, in velocity of water during flow in the nozzle is depicted in Figure 5. The figure shows that velocity increased with increasing in pressures proportion relationship, which clearly explains that the groove has no effect on velocity as it increases due to increase in pressure. This is because the groove reduces the velocity by increasing surface area.

Figure 6 shows the effect of groove dimensions $1\times1$ (mm) and location 15 mm at 8 bar, 10 bar and 12 bars, in velocity of water during flow in the nozzle. The representation shows that velocity increased with increase in pressures proportion relationship. Therefore, it can be stated that the groove has no effect and velocity mainly increases due to increasing pressure as the groove reduces the velocity by increasing surface area.

Figure 7 illustrates the effect of groove dimensions $2\times2$ (mm) and location 10 mm at 8 bar, 10 bar and 12 bars, in velocity of water during flow in the nozzle. The velocity and pressure increase in a proportional relationship. The figure clearly shows that groove has no effect on the velocity because the groove reduces the velocity by increasing surface area.

Figure 8 shows the effect of groove dimensions $2\times2$ (mm) and location 15 mm at 8 bar, 10 bar and 12 bars, in velocity of water during flow in the nozzle. This figure shows no effect on velocity because the groove reduces the velocity by increasing surface area.
Figure 9 illustrates the effect of double rings dimensions 1×1 (mm) and location 7 mm for the first and 15 mm for the second ring from the exit at 8 bar, 10 bar and 12 bars, in velocity of water during flow in the nozzle. The velocity increased with increasing pressures in a proportional relationship. There was no effect of increasing pressure on the velocity because the groove reduces the velocity as the surface area increased.

Similar to the previous settings, Figure 10 also shows proportional relationship between increasing velocity and pressure. The results clearly demonstrate that there is negative effect of all dimensions and distance of groove location on the velocity of water during flow, at different pressure 8, 10, and 12 bar. This might be due to increase in surface area that decreases the velocity. There is no significant effect of groove on the velocities and turbulence intensities, as observed by comparing the corresponding plots because of experiencing much stress across the nozzle all the way up to the ringed nozzle exit. These results are in agreement with Yu et al. [5] as the study reported little effect of groove extending or exit the nozzle on the characteristics of fluid flow. It is of significance, as understanding it will help in considering its effect in firefighting, so that necessary changes in the model can be suggested.

The aerodynamic performance of micro lobed nozzles ejectors of different dimensions was compared in an experimental and numerical study by Shan et al. [25]. The study used the k-ε standard turbulence model based on Reynolds-Averaged Navier-Stokes (RANS) simulations and showed significant impact of nozzle shape on the fluid downstream. Another similar study by Babu and Mahesh [26] studied the impact of inflow condition on the ambient fluid exiting the nozzle in a jet. The study failed to emphasize on the significance of initial conditions as the fluid exits the nozzle. On the contrary, the present study has drawn numerous findings and conclusions regarding certain physical and methodological aspects of fluid flow through a nozzle. The study also showed significant impact of nozzle shape on the exit conditions in the post-contraction region. A similar study by Yu et al. [5] compared the experimental data to investigate the impact of nozzle geometry on the turbulence characteristics of fluid flow through the nozzles. It is also likely that the analytical model of the pressure attributes is authentic and beneficial to obtain an insight of the physical mechanism [27]. Moreover, the passive control device can control the base pressure, which result in an improvement in the base pressure and mitigating the base drag. In addition, passive control is very effective and efficient whenever there is preferable pressure gradient at the nozzle exit [28, 29]. The results demonstrated that presence of ring required increased inlet pressure for moving fluid through the nozzle as it increases the mean velocity and turbulence at the exit. These results are somewhat consistent with the present study that showed rings modifying the nozzle shape have significant impact on velocity.
CONCLUSION

The present study has investigated the effect of different nozzle shapes on fluid flow characteristics in firefighting nozzles. There was no effect of groove design with dimensions 1×1 (mm) and location 15 mm at 8 bar, 10 bar and 12 bar because increase in surface area reduces the fluid velocity. These results demonstrate that there is no effect of the nozzle modified with grooves on the fluid velocity. These results exhibit good expectations about the use of rings to increase velocity of water that further improve nozzles operation in the same dimension.

The study has demonstrated that flow quantities in any region were not changed by extending the nozzle by one nozzle exit diameter. Slight change in the wall pressure is likely to be observed by cutting groove in the proximity of exit. This is clearly explained by the present study as addition of ring changes the pressure field in the post-contraction zone. The baseline nozzle with same flow rate imposed on nozzle was not effective in increasing the mean velocity of fluid in the jet. These findings suggest that inserting grooves without rings do not present promising results in achieving higher mixing efficiencies in the baseline nozzle, as it creates exit flow that is conducive to mixing. However, the future studies need to use the model developed in this study to assess the effect of water separations on velocity with inclusion of more grooves along with rings.

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