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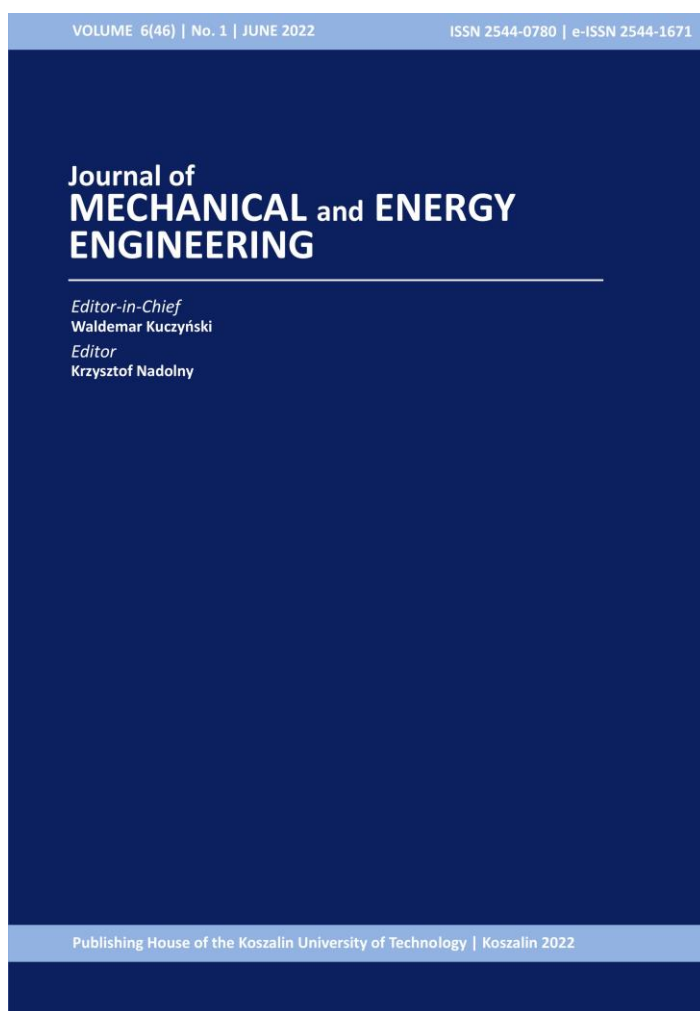
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DOI: 10.30464/jmee.2022.6.1.7

## Cite this article as:

Bansode V.; Verma M.; Pandhare A.; Shinde S. Prediction of cavitation inside mini-sac Diesel injector nozzle using computational fluid dynamics. Journal of Mechanical and Energy Engineering, Vol. 6(46), No. 1, 2022, pp. 7-12.



**Journal of Mechanical and Energy  
Engineering**

**Website:** [jmee.tu.koszalin.pl](http://jmee.tu.koszalin.pl)

**ISSN (Print):** 2544-0780

**ISSN (Online):** 2544-1671

**Volume:** 6(46)

**Number:** 1

**Year:** 2022

**Pages:** 7-12

## Article Info:

Received 16 February 2022

Accepted 2 March 2022

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# PREDICTION OF CAVITATION INSIDE MINI-SAC DIESEL INJECTOR NOZZLE USING COMPUTATIONAL FLUID DYNAMICS

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*(Received 16 February 2022, Accepted 2 March 2022)*

**Abstract:** The performance of the internal flow of the fuel injector is impeded by several factors. The nozzle is one of the factors, being typically about a millimeter long and a fraction of a millimeter in diameter. Cavitation inside the diesel injector nozzle is associated with local pressure distribution. At flow areas with sharp corners, the pressure may locally drop below vapour pressure. The aim of this study is to assess the impact of turbulence and cavitation models on the prediction of flow in diesel injection nozzle. In the present study, an analysis of an existing 6 hole mini-sac diesel injector nozzle is carried out using a CFD package. The main objective of the research is to design a nozzle to avoid cavitation and to find out the contribution of different parameters through parametric study. Cavitation is a complex phenomenon whose appearance depends on the physical as well as flow properties of the flowing substance. Thus, for a better visualization of cavitation, a 3D CFD simulation of mini-sac injector nozzle is carried out. An analysis of a single nozzle hole of a mini-sac diesel injector nozzle is considered for the analysis, as the flow is uniformly distributed through each nozzle. As the three-dimensional geometry of mini-sac nozzle is complicated, therefore tet/hybrid element with T-Grid meshing scheme is used, for good surface meshing. The analysis is carried out at injection pressure of 500 bar. The CFD results are validated against test data with the maximum deviation for the mass flow rate of 8.67% at full needle lift.

**Keywords:** cavitations, mini-sac diesel injector nozzle, needle lift, parametric study, CFD.

## 1. INTRODUCTION

The injection nozzle is the most important for engineering applications relating to the fuel injection system. The inner flow through an injection nozzle is a very important factor for spray formation and atomization generated by the nozzle, and it is related to the combustion potency and the resultant formation of pollutants. An intensive understanding of the complicated nature of flow into the nozzle and flow contagious to the nozzle is critical for predicting spray development [1]. In turn, cavitation occurs within the diesel nozzle because of a pressure drop below the saturated vapor pressure that is

additionally known to attenuate the combustion efficiency directly and indirectly.

Computational Fluid Dynamics has proved its importance in recent years; this is a simulation tool for modeling thermal and fluid flow problems [2]. Fuel injection duration and injection pressure do not play any great role in the dynamic formation of the varying cavitation patterns [3]. The CFD model provides information about the local flow field at the location of the vortex. Vortex cavitation is a source of a cycle to cycle and spray to spray variation in diesel fuel injectors [4].

Cavitation and gas entrapment inside the injector nozzle orifice can greatly affect the local and global behavior of the flow. For a given complicated nature

of the nozzle, several investigations have focused on the internal nozzle flow. Once the nozzle flow is understood, spray breakup may become a more tractable problem. However, the details of the flow through the nozzle are quite complicated and have become a field of study on their own. The study of the internal nozzle flow includes turbulence, developing pipe flow and cavitation [5]. The ultimate goal of the nozzle is to produce spray and so our current approach begins with understanding the spray. The present study focused on the development of a CFD model for cavitation.

Numerical analysis of minisac diesel injector nozzle is performed using FLUENT 6.3.26 CFD package to study vapour distribution along nozzle hole and amount of vapor fraction for given pressure range.

For a different needle lift, mass flow rate at the outlet is calculated for a steady state condition and validated against test data. Finally, a CFD analysis of minisac nozzle for unsteady condition is done and parametric study is carried out for the selection of an optimum combination of geometrical parameters to minimize cavitation.

## 2. THEORETICAL BACKGROUND

In the present analysis, a six hole nozzle with sac volume is considered with all the dimensions in mm, and it is shown in Figure 1. The nozzle is consisting of six holes and each hole located axe-symmetrically. Therefore, only a single nozzle hole is considered for the analysis to minimize the computational efforts.

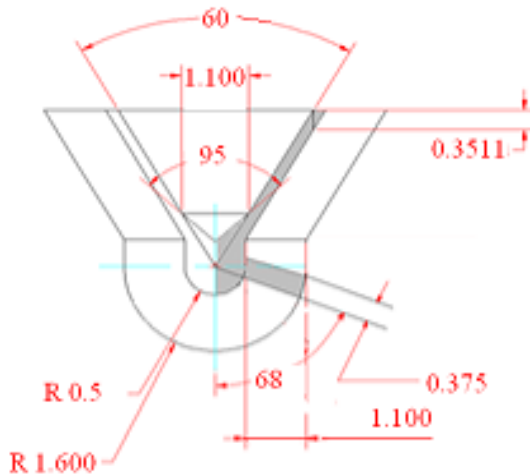


Fig. 1. Geometry of mini-sac nozzle

## 3. ANALYSIS

The analysis is carried out analytically and numerically. The analytical solution is used to calculate the reference mass flow rate at the outlet,

and the numerical solution provides the vapour fraction along the nozzle hole.

### 3.1. Analytical solution

The analytical calculation is done with a simple nozzle flow. Therefore, the reference mass flow  $M_{ref}$  is calculated using the Bernoulli equation. The value of the coefficient of discharge is calculated from the correlation reported by Martynov [1].

#### 1. Value of $C_d$ .

The value of the coefficient of discharge is calculated from the cavitation number.  $P_2$  and  $P_1$  are inlet and outlet pressures respectively.

$$CN = \frac{(p_2 - p_v)}{(p_1 - p_v)} = \frac{500 - 5}{5 - 0.054} = 99.98. \quad (1)$$

#### 2. Velocity at the outlet.

Pressure drop:

$$\Delta P = 495 \times 105 \text{ Pa}. \quad (2)$$

Coefficient of discharge is equal to:

$$C_d = 0.67, \quad (3)$$

$$\rho = 832 \text{ Kg/m}^2, \quad (4)$$

$$A = 0.11046 \text{ mm}^2, \quad (5)$$

$$V = C_d \sqrt{\frac{2 \times \Delta P}{\rho}} = \quad (6)$$

$$0.67 \times \sqrt{\frac{2 \times 495 \times 10^5}{832}} = 231.116 \frac{\text{m}}{\text{s}}.$$

#### 3. Mass flow rate at the outlet.

Mass flow rate is equal to:

$$\rho AV = 832 \times 0.11046 \times \times 10^{-6} \times 231.116 = 0.0212 \text{ Kg/s}. \quad (7)$$

### 3.2. CFD solution

The analysis is done using the CFD code. The steps in the analysis include geometry creation, meshing, assigning boundary conditions, a solution and post-processing. In the geometry creation and meshing, the nozzle geometry is modelled and divided in small elements with an interval size of 0.8. After that, assigning boundary conditions and domain defining is carried out. Then, the system is imported to a suitable solver to solve it using a different physical model. In post-processing, various parameters are predicted to obtain more details about the results. The present system is analysed using the abovementioned steps with a proper model as follows.

### 3.3. Computational model

To analyse the flow characteristics of the in-nozzle flow, the 3D axisymmetric single nozzle is considered as a continuum. The nozzle was modelled using GAMBIT 2.3.16 and meshing was done with a tet/hybrid element and a T-Grid meshing scheme for good surface meshing. As the

dimensions of the nozzle are in millimetres, the interval size was selected to be 0.8. The meshed geometry is as shown in Figure 2.

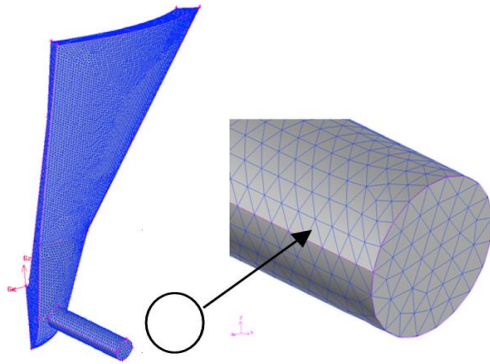


Fig. 2. Meshing of Mini-sac Nozzle

**Initial and boundary conditions**

In the present analysis, the pressures at the inlet and at the outlet are specified with the pressures of 500 and 5 bar respectively with a temperature of 300 K and a vaporization pressure of 5400 Pa. The density and viscosity of diesel is 832 kg/m<sup>3</sup> and 0.0065. The commercial code consists of different solver models such as turbulence, radiation and phase change. In the present analysis, the reference velocity indicates higher turbulent flows. Therefore, a standard *K-ε* model was employed in the analysis [4]. The boundary assigned conditions are shown in Figure 3. Then model is imported to a fluent with assigned boundary conditions.

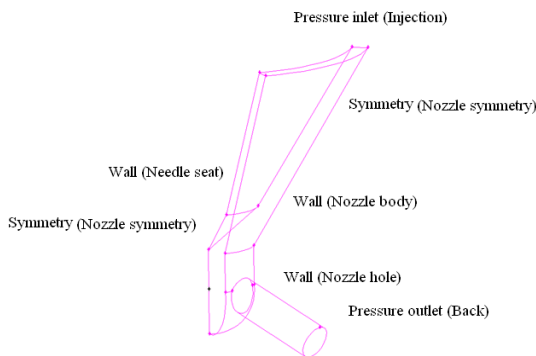


Fig. 3. Boundary Conditions Assigned to Nozzle

**Results and discussion**

The performance prediction for the mass flow rate with different needle lifts at a steady state condition is carried out. The variation of the needle lift Vs mass flow rate is presented in Figure 4. It is observed over the full needle lift in the maximum variation in the predicted and experimental results, and it is 8.67%.

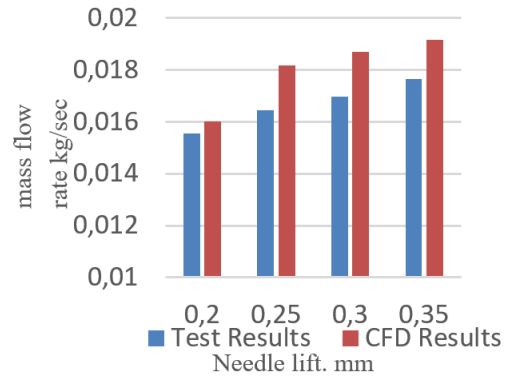


Fig. 4. Variation of needle lift Vs mass flow rate

The pressure and vapour distribution along the nozzle length is presented in Figure 5 and 6. The cavitation formation is obtained at the solid boundary of the nozzle hole.

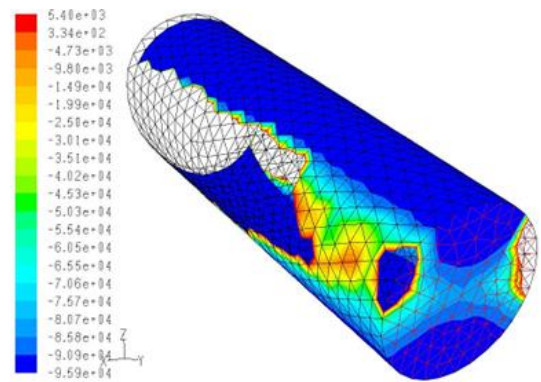


Fig. 5. Pressure (in Pa) contour plot

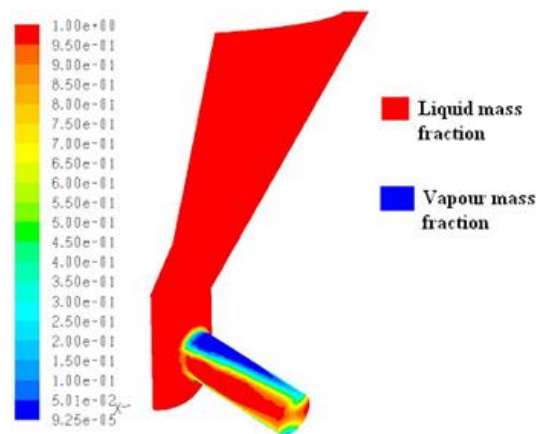


Fig. 6. Phase contour plot

**Parametric study**

As cavitation occurs along the nozzle hole, there is need to study the influence of different parameters. There are different geometrical parameters considered for parametric study such as

the sac volume, the nozzle hole angle and the corner radius to predict the cavitation (Fig.7 to 12).

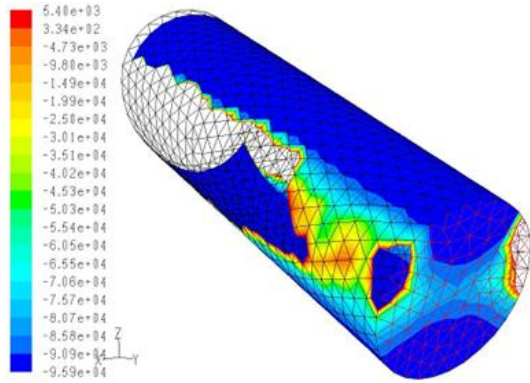


Fig. 7. Pressure (in Pa.) contours for 0.5 mm, 0 mm & 68°

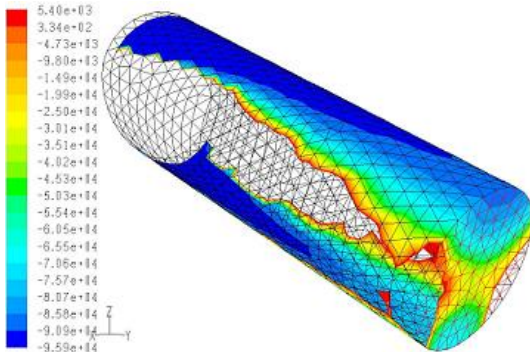


Fig. 8. Pressure (in Pa.) contours for 0.475 mm, 0 mm & 68°

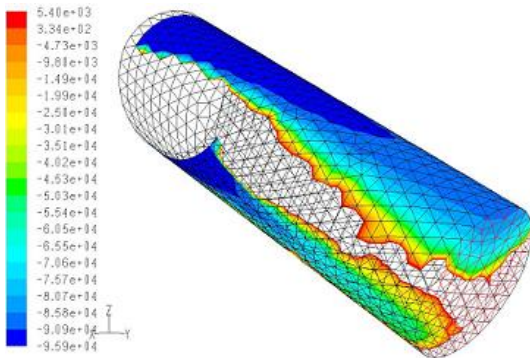


Fig. 9. Pressure (in Pa.) contours for 0.475 mm, 0 mm & 65°

Figures indicate that the formation of cavitation mostly along the nozzle hole length near the solid boundary is due to abrupt changes in the flow path while the fuel travels from the sac area to the nozzle hole inlet. In the figure, the nomenclature of the first fraction and of the second fraction corresponds to the sac volume radius and the corner radius respectively. The last number indicates the nozzle hole angle.

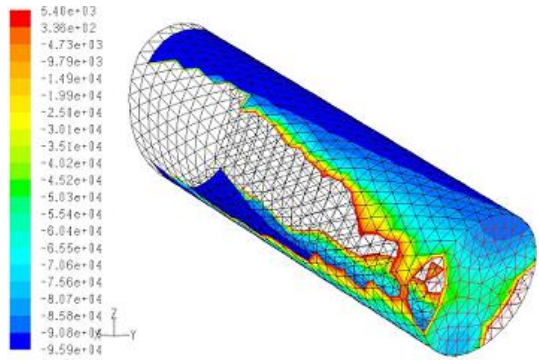


Fig. 10. Pressure (in Pa.) contours for 0.5 mm, 0 mm & 62°

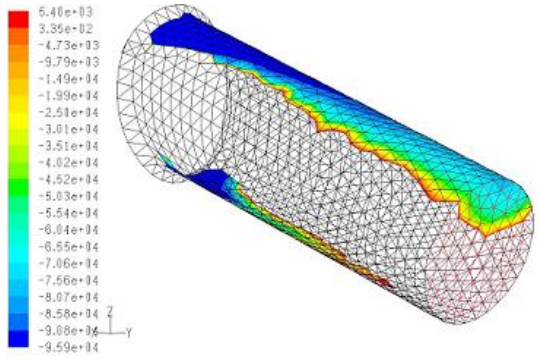


Fig. 11. Pressure (in Pa.) contours for 0.5 mm, 0.375 mm & 65°

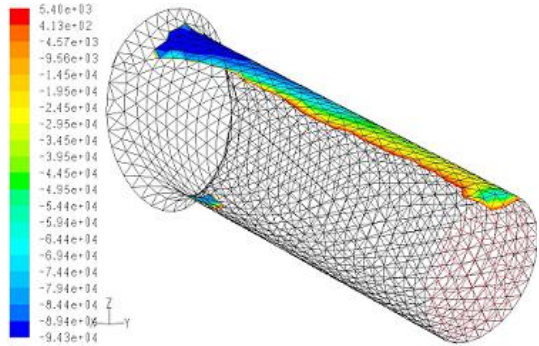


Fig. 12. Pressure (in Pa.) contours for 0.5 mm, 0.75 mm & 65°

Figure 13 shows the graph of a combined effect of the parameters on cavitation. It is useful to select the combination with minimum cavitation.

From the graph, it is evident that the corner radius plays an important role to minimize cavitation. From the viewpoint of the nozzle hole angle, it is difficult to predict the role of the nozzle hole angle for different sac volumes and different corner radiuses.

#### 4. TEST RESULTS

For the injector nozzle, both Charged Coupled Device (CCD) images and Laser Doppler



Velocimetry (LDV) measurements are used. The velocity obtained at different vertical planes is shown in Figure 14. The mean axial velocity component in the direction of the hole axis was measured. The results were presented for the flow of fully developed cavitation. The plotted velocity was normalized with the mean injection velocity ( $U_{injection}$ ) derived from the flow rate and the hole cross-sectional area. The computational results were presented at respective locations. Test cases are shown in Table 1.

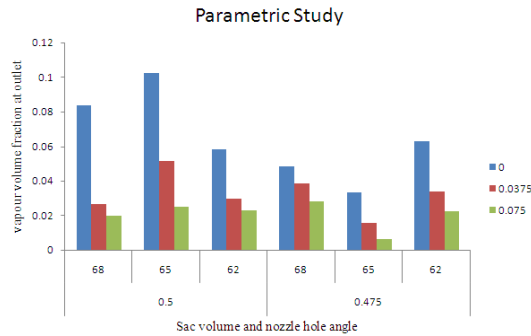


Fig. 13. Comparison of different combinations of parameter for minimizing of cavitation

Tab. 1. Test Cases Used for Validation

Large scale	Cavitation No.	$P_{injection}$ (bar)	$U_{injection}$ (m/s)	Flow regime
	1.49	3.0	16.0	Fully developed

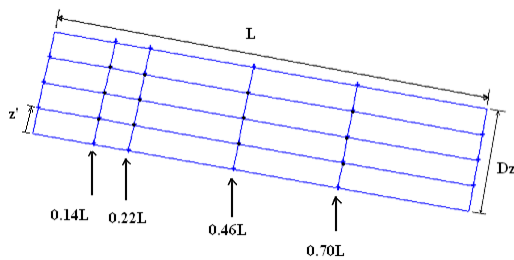


Fig. 14. Numerical Grid and LDV Measurement Planes for Velocity Calculation along Nozzle Hole Length

## 5. CONCLUSIONS

The methodology is extended to predict the performance of a given mini-sac diesel injector nozzle and it is assessed against both test and analytical results. Also, a parametric study was performed to predict the performance of a given mini-sac diesel injector nozzle over a range of geometrical parameters.

The following conclusions are made based on the CFD results obtained:

1. A larger sac volume has always a problem of dribbling; therefore, from that point of view, the radius of the sac volume is reduced to 5%, and it shows an effect of cavitation. Figures 6a and 6b indicate that less cavitation occurred at the minimum sac volume area.
2. In the analysis, the nozzle hole angle was reduced up to 10% and its effect on cavitation was analysed. It is difficult to predict the effect of the nozzle hole angle on cavitation. However, it was observed that the minimum cavitation occurred for the nozzle cone angle of 65°, which is quite obvious from the comparisons of Figures 6b, 6c and 6d.
3. In the case of the corner radius, the corner radius was increased in the relation to the nozzle hole diameter ( $CR = 0, 0.1$  and  $0.2 D$ ) and the effect of the corner radius is analysed in Figures 6d, 6e and 6f. It indicates that the role of the corner radius is more dominant for minimizing cavitation.
4. For given geometry and boundary conditions, the 65° nozzle hole angle gives minimum cavitation for the sac volume of 0.475 mm and maximum cavitation for 0.5 mm with the corner radius.
5. The minimum vapour fraction is observed for a combination of the 0.475 mm sac volume with the 65° hole angle and the 0.075 mm corner radius.

## 6. FUTURE SCOPE

The present work can be extended to study the effect of variation in the nozzle hole diameter and the nozzle hole length. In the present study, an analysis is carried out with fixed needle lift. It may be possible to analyze the cavitation inside the nozzle with transient needle lift.

## Acknowledgements

Part of this work was supported by the Mahindra and Mahindra Group. The Author would like to thank Mr Shrinath Korgaonkar from Walchand College of Engineering Sangli. Special thanks to Dr. B. S. Gawali, Professor, Walchand College of Engineering Sangli.

## Nomenclature

### Acronyms

CFD	- Computational Fluid Dynamics
LDV	- Laser Doppler Velocimetry
CCD	- Charged Coupled Device

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