Numerical Analysis of Scallop Shapes on Performance of Lobed Nozzle

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ABSTRACT

The infrared suppressor used in the exhaust system of turbofan engines, turbojet engines and turboprop engines generally has a lobed nozzle to pump cool air from the outside and mix it with the hot exhaust gas from the engine. The lobed nozzle mixes the primary and secondary streams with high effectiveness but induces low pressure loss has been widely used for heat and mass transfer in the fluid engineering field. The primary parameters used to evaluate the performances of the lobed nozzle include pumping performance, mixing effectiveness, and pressure loss. Higher pumping performance, higher mixing effectiveness, and lower pressure loss indicate that more cool air is pumped, the mixing with the hot exhaust is more effective, and there is less energy loss. The present study shows that double triangle scalloped nozzles has high mixing effectiveness than all other scalloped nozzles considered in the project work.

Keywords: Lobed nozzle, infrared radiation, infrared suppression, infrared seekers, mixing effectiveness, pressure loss

INTRODUCTION:

The word camouflage has its origin in the french word camoufler which means to disguise. During wars military equipments and men are required to hide or avoid the detection from their enemy. This is required to reduce threat of losing or to invoke a surprise attack on enemy. There were no equipments or sensing technology available during early days for sensing the threat from enemies.

This technique was first employed in early times of world war-I in order evade the detection from enemy. And this became a widely known and to be used by all countries during world war-II. During war army needs to protect its equipment and its soldiers as well. This led to a major breakthrough for the development in the stealth technology by evading detection[1]. The demand for countermeasures has increased as the technologies involved in detecting electro-magnetic spectrum become more advanced.

Nowadays the advancement in technology has led to camouflage of high speed objects like helicopters, submarines etc. The so called stealth helicopters operate on the above principle by reducing its heat signature. The mechanism used at the nozzle exit to suppress the temperature is called 'infrared suppression'. This reduces the threat from missiles which seek heat signatures. The technology where vehicle goes undetected on enemy's radar is called as stealth. Infrared suppression also enables noise suppression caused due to friction between hot core and secondary flow. Hence suppression means employed will also cause infrared signature to be reduced. This is evident from the latest high bypass turbofan engines. They are also called by the names ejectors, exhaust mixers or lobed nozzles.

The suppression techniques are employed for evading the detection. There are various techniques employed for suppression of radiations emitted due to heat signature. The following techniques are used nowadays: Ejector dilution, Fan augmented dilution, Swirl augmented dilution, Clean exhaust gases, Thick film cooling, Thin film cooling, Hiding view with insulation, Surface emissivity control.

In case of turbofan engines secondary air is forced into mixer through a bypass channel. Bypass ratio for old type of engines was less and this led to larger heat signatures and also produces high noise. But the latest engines uses high bypass ratios to overcome the noise and also to reduce high emission temperatures. High bypass ratio also increases efficiency of the engine because the mass flow rate of the secondary stream is more than the core stream and shear layer produced between core and secondary stream enhances the momentum transfer. This in turn reduces the fuel required for the thrust at take off and at cruising speed. Lobed mixers are passive type of infrared suppressors. Lobed mixers do not use any moving parts and hence they are considered as most effective in mixing secondary stream with the core stream. Lobed mixers development over many decades to the latest high mixing effectiveness is shown in figure 1.

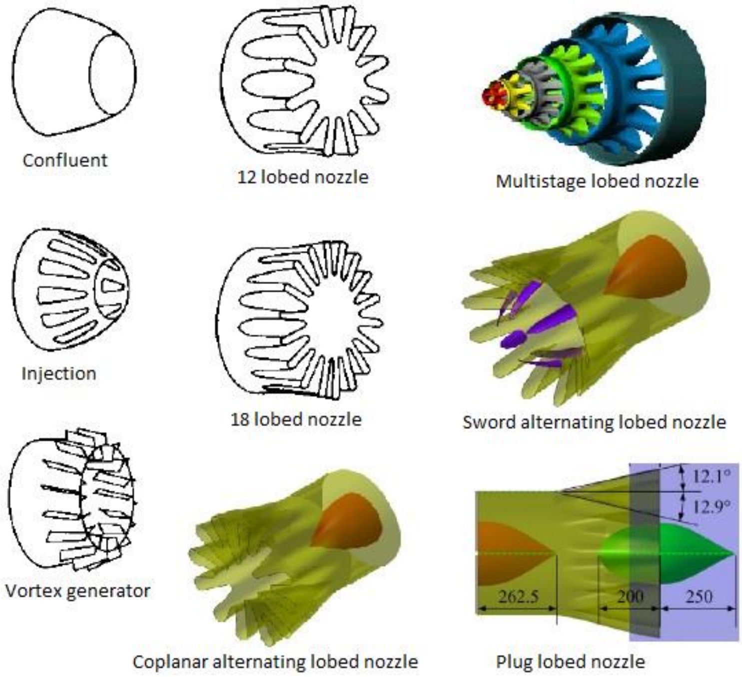


Fig.1 Types of lobed nozzle

LITERATURE SURVEY:

Infrared signature suppression:

"Infrared signature suppression is the technology used in military vehicles to suppress the thermal signature emitted from the exhaust system into atmosphere". If the aircraft has to cruise in atmosphere for long duration without detection from enemy detection systems it must be incorporated itself with less thermal signature producing exhaust systems. Infrared signature suppression is essential for warships. One must also find ways to reduce the temperature at the tail ends because thermal signatures are also produced to heating of the tail end parts by exhaust gases. There are two types of infrared suppressors [3]: Active suppressor and Passive suppressor. 'Active suppressor' uses moving mechanism powered by separate motor or the engine itself. This type of suppressors are generally not feasible due to moving parts involved in suppression system, because moving parts operate abruptly at high speed and also it reduces efficiency of the engine[2]. 'Passive suppressor' utilizes the design alterations like lobed nozzles to mix atmosphere air with exhaust.

Multilobed mixers have become popular as low loss mixing elements in a variety of fluid mechanical applications. Such devices are exploited in turbofan engines where hot turbine flow is mixed with cooler fan flow prior to exhaust improving performance and reducing noise for many turbofan cycles. The lobed nozzles can be classified based on the number lobes like six, twelve, eighteen and twenty four lobed nozzles as shown in figure 2.6. Based on method of mixing it can be classified as plug lobed nozzle, coplanar alternating lobed nozzle, sword alternating lobed nozzle etc. Overall gain depends upon the balance between increased mixing and extra pressure losses[3].

A six lobed nozzle as shown in Fig.2 was used for experiment which has 25□ inward penetration angle and 14□ outward penetration angle. Jet at velocity of 20 m/s enters from duct of diameter 40mm. A six lobed nozzle was used for numerical model validation.

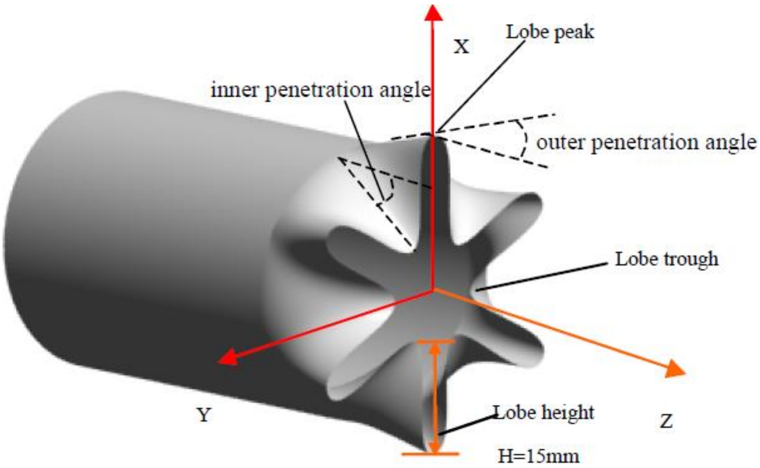


Fig.2 Six lobed nozzle used in DP-SPIV experiment

Project statement:
As we see from the above research papers, a very little detail is available considering scalloped and scarfed types of mixer. From paper "configuration of lobed nozzle for high mixing effectiveness" it can be seen that the author has performed study on scalloped nozzle considering a single 40□ cut. Analysis conducted by R Mao depicts the effect of nozzle tip shapes on the performance of mixer. Currently there are no studies with focus on scallop shapes. Hence the present study reflects the effects of different scallop shapes on the performance of the lobed nozzles. Performance of lobed mixers is evaluated using parameters developed by Yi Xie. Therefore title of the current project work is "Numerical analysis of scallop shapes on performance of lobed nozzle".

Scope of the Study:
Lobed nozzle mixers can be utilized in two ways one as infrared suppressor and other as noise suppressor. For present work we will only consider thermal based analysis. Future commercial applications of the turbofan engine will be required to meet increasingly stringent noise abatement criteria, primarily, due to an increase in aircraft traffic near airports. Many of the current turbofan engines are based on thermodynamic cycles with a bypass ratio of five to six as opposed to the lower bypass ratio of 1.5 or so in older engines. With very high mixed jet velocities for older lower bypass engines, jet-noise is a dominant contributor to total engine generated noise, especially at take-off (TO). However, even with the current higher bypass ratios, and consequently reduced mixed jet velocities, jet noise continues to be a significant contributor[4]. Mixing efficiency plays only part in reducing the noise and infrared signature. Hence the other factors which are not considered in the present work also plays important role. The following major highlights of the present proposed work.

1. Fast mixing is achieved at trailing edge by scalloping of lobes.
2. Vortex formation into stream can be controlled by spoilers.
3. Increase in mixing effectiveness.

RESEARCH METHODOLOGY:
Ansys CFX was used for solving and interpreting the results. Before solving, all the required boundary conditions are applied in the CFX-Pre. The shear stress transport model is used for solving the present problem.
The shear-stress transport (SST) k-□ model was developed by Menter to effectively blend the robust and accurate formulation of the k-□ model in the near-wall region with the free stream independence of the k-□ model in the far field. These features make the SST k-□ model more accurate and reliable for a wider class of flows (for example, adverse pressure gradient flows, airfoils, and transonic shock waves) than the standard k-□ model.

Transport equations for the SST k-ω model:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left(\Gamma_k\frac{\partial k}{\partial x_j}\right)+G_k-Y_k+S_k$$

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_j}\left(\rho\omega u_j\right)=\frac{\partial}{\partial x_j}\left(\Gamma_\omega\frac{\partial\omega}{\partial x_j}\right)+G_\omega-Y_\omega+D_\omega+S_\omega$$

Geometric model:

The complete model with domain is as shown in Fig.3. All the necessary dimensions of the model are also shown. A 'C' shaped domain large enough to capture flow variations is made to surround the Lobed Nozzle. Only 30o sector of the model is considered for the simulation because the model has 12 equal sectors which can be modeled and analyzed by considering a single sector of 30o. This avoids the flow disturbances created by other walls. Also 30□ sector uses less number of mesh elements than full 360□ model and the time required for solving the flow problem decreases to 1/12th of the total time.

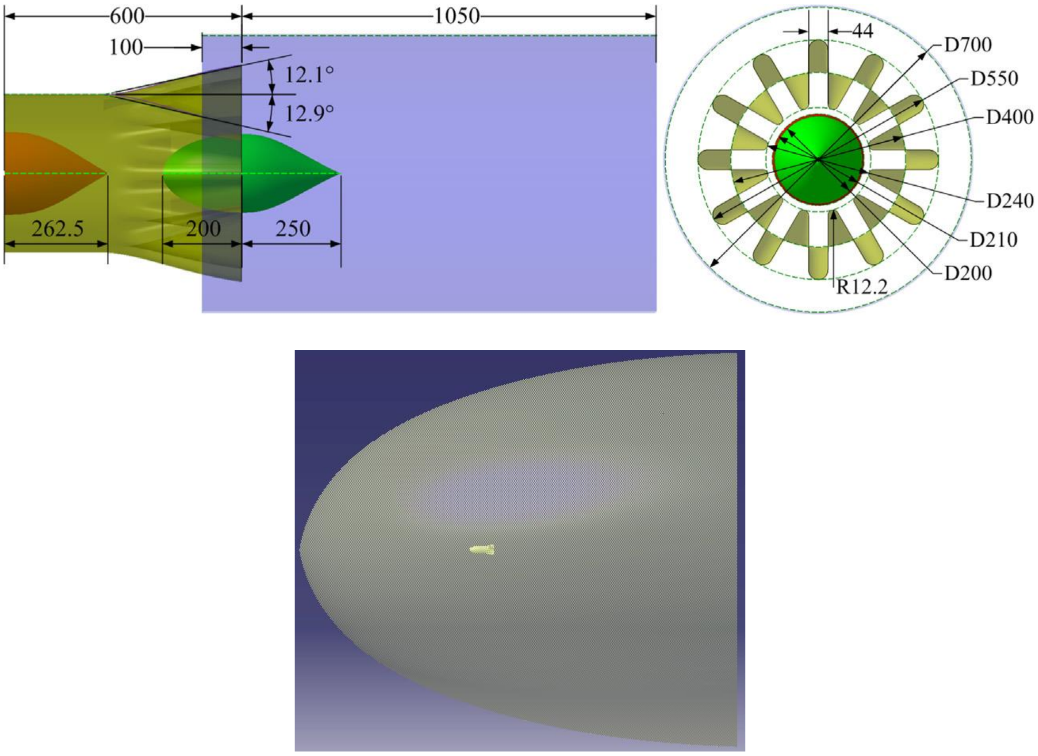
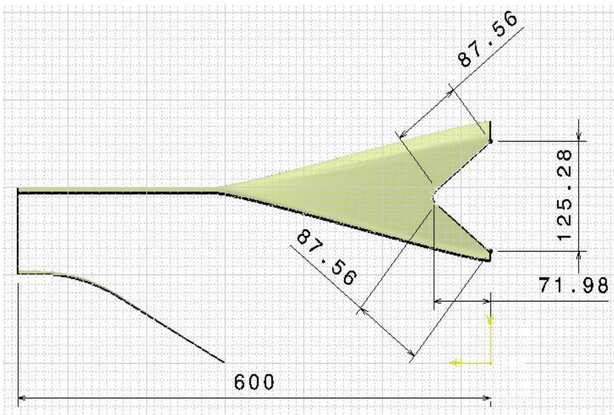


Fig.3 Lobed Nozzle with dimensions

To study the effect of scallop on performance of lobed nozzle, we need to remove some portion of the side wall of lobes. The scallop operation has to be performed in such a way that there should not be any large drop in pressure in mixing stream. Lobes are scalloped in triangle and semicircle shapes and finally lobe tip will also be scalloped and the performances of all nozzles are compared against each other.



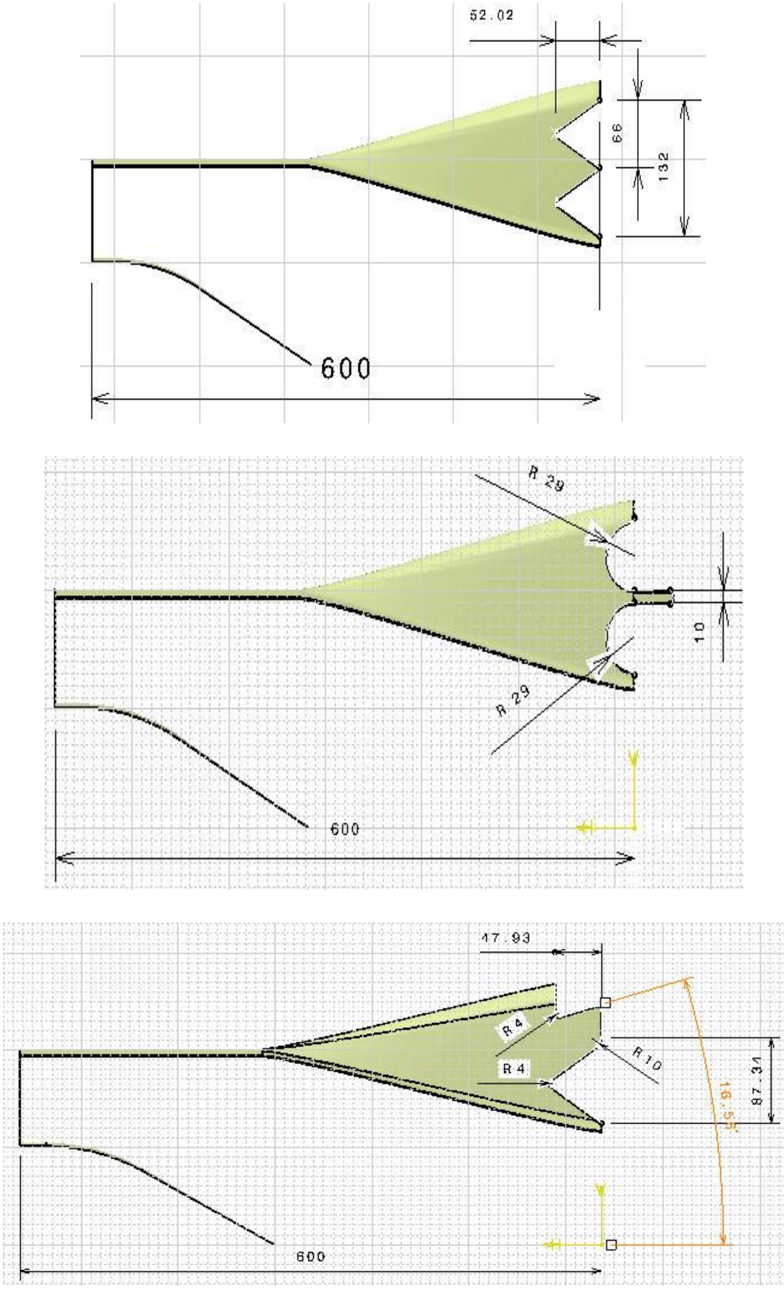


Fig.4 Scallop shapes for analysis

Meshing:

One of the reasons to consider only 30□ sector of the model is to reduce the time consumption for meshing. It reduces the time and also the memory required to 1/12th of the total. Periodic boundary condition is used so that the result can be interpreted as whole model while interpreting the results.

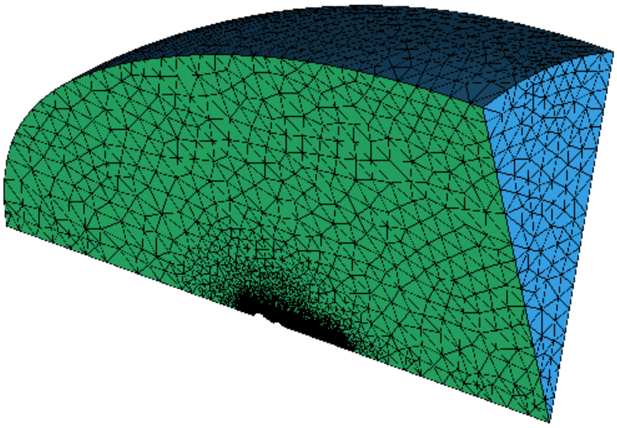


Fig.5 Mesh 30o sector

Table 1 Boundary Conditions

Inlet Velocity	125 m/s
Inlet Temperature	850 K
Atmospheric Pressure	101325 Pa
Atmospheric Temperature	300 K
Inlet Turbulent Intensity	5%
AtmosphereTurbulent Intensity	5%

Performance Parameters:

Pumping performance: The pumping ratio Φ [7] was used to assess the pumping performance of the lobed nozzle, and is defined as:

$$\Phi = \frac{m_s}{m_p}$$

where mp is the "mass flow rate of the primary stream", and ms is the "mass flow rate of the secondary stream". The pumping ratio of plugged lobed nozzle is higher compared with any other lobed nozzle types.

Mixing effectiveness: The thermal mixing efficiency (ηtr) [7]can be used to evaluate the mixing effectiveness of the lobed nozzle.

$$\eta_{tr} = 1 - \frac{\int (T_m - T_M)^2 dm_m}{T_p^2 m_p + T_s^2 m_s - T_M^2 m_m}$$

where "mm is the mass flow rate of the mixing stream, TP is the initial temperature of the primary stream, TS is the initial temperature of the secondary stream, Tm is the temperature of the mixing stream, and TM is the temperature after complete mixing of the primary and secondary streams", TM can be calculated as shown in the below equation[5]. TM remains constant for constant velocity inlet condition.

$$T_M = \frac{T_p m_p + T_s m_s}{m_m}$$

Total pressure recovery coefficient: The total pressure recovery coefficient σ is an indication of how much pressure loss is induced by jet mixing and is defined as

$$\sigma = \frac{\int P_m^* dm_m}{\int P_p^* dm_p + \int P_s^* dm_s}$$

Where P*p is the initial total pressure of the primary stream, P*s is the initial total pressure of the secondary stream, and P*m is the total pressure of the mixing stream.
Vorticity: The non-dimensional streamwise vorticity ωx defined as:

$$\omega_x = \frac{D}{u_p}\left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right)$$

Numerical Validation:
The numerical model is validated by comparing velocity vector distribution and vorticity against the experimental results. Hu conducted experiment on 6 lobed nozzle having 6mm width and 15mm height. Lobes have 25o inward penetration angle and 14o outward penetration angle. The stream enters the nozzle through a duct of diameter of 40mm. The Reynolds number of the flow is 55000.
The experimental method called "dual-plane stereoscopic particle image velocimetry (DP-SPIV)" was used for measuring the flow field. The results are obtained at distances of 20mm, 40mm and 60mm from the exit nozzle. Figures 3.18, 3.19 and 3.20 shows comparison of velocity at different planes normal to x direction. Figure 3.21 represents the mixing decay of maximum value of the streamwise vorticity and normal vorticity in the Hu's experimental method. Figure 3.22 represents the decay of streamwise vorticity in numerical simulation and figure 3.23 represents the decay of normal vorticity in numerical simulation.

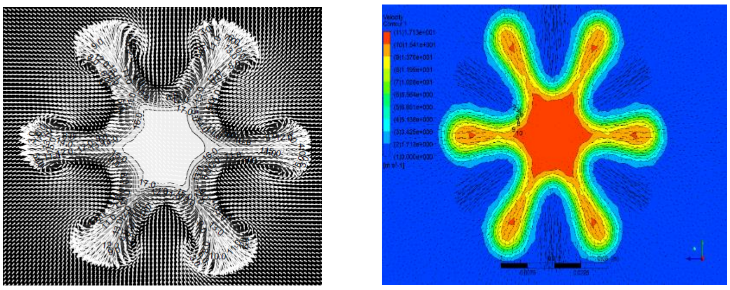


Fig.6 Velocity field at 20mm of DP-SPIV and numerical model respectively

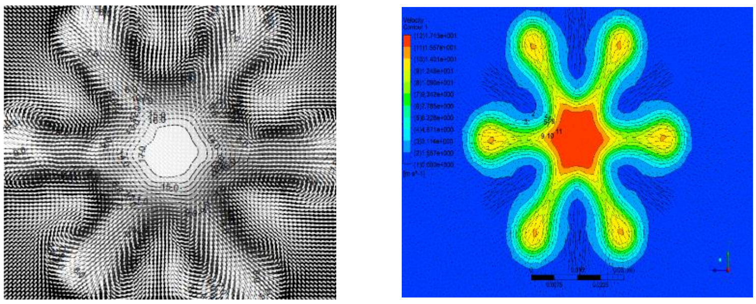


Fig.7 Velocity field at 60mm of DP-SPIV and numerical model respectively

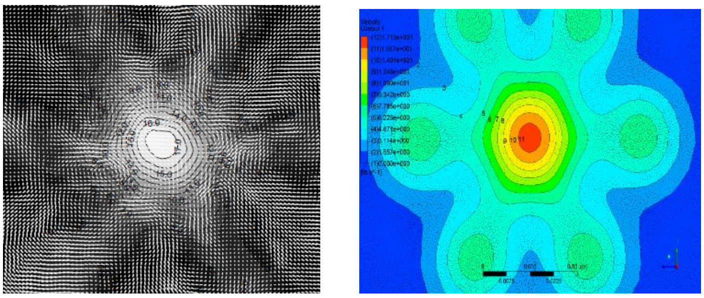


Fig.8 Velocity field at 120mm of DP-SPIV and numerical model respectively

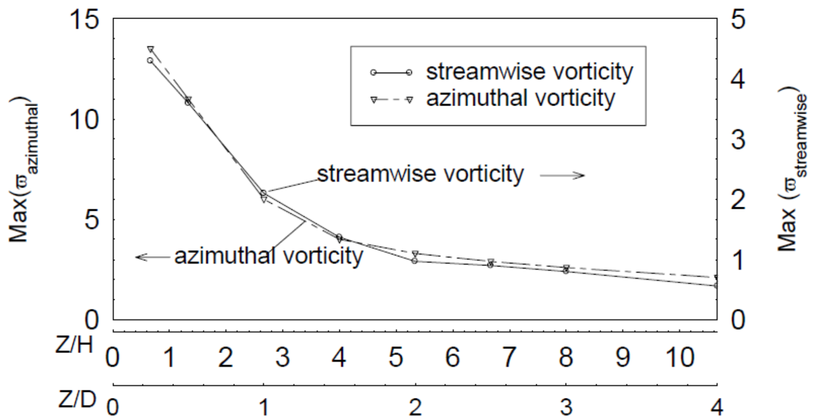


Fig.9 Decay of streamwise and normal vorticity in DP-SPIV

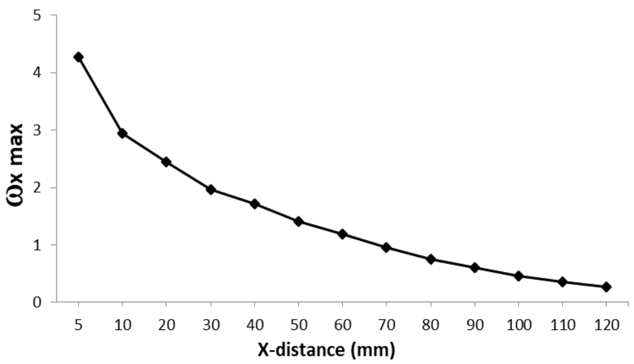


Fig.10 Decay of streamwise vorticity in numerical model

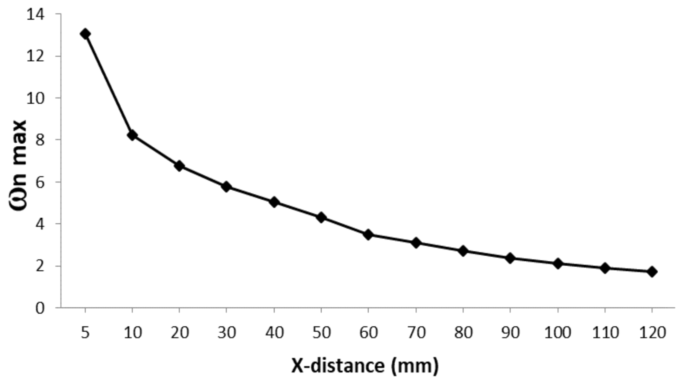


Fig.11 Decay of normal vorticity in numerical model

Figure 3.24 compares the stream wise vorticity field between experimental method and numerical method. Figure 3.25 compares the normal vorticity field between experimental method and numerical method at distance of 20mm from nozzle exit in x direction. From all the above comparisons it is evident that the present numerical model is valid and matches well with the Hu's experimental results.

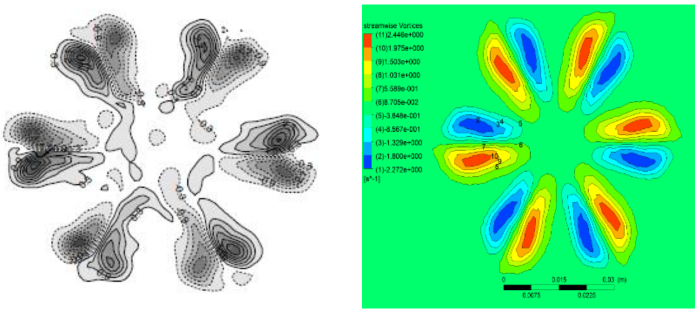


Fig.12 Streamwise vorticity field at 20mm in DP-SPIV and numerical model

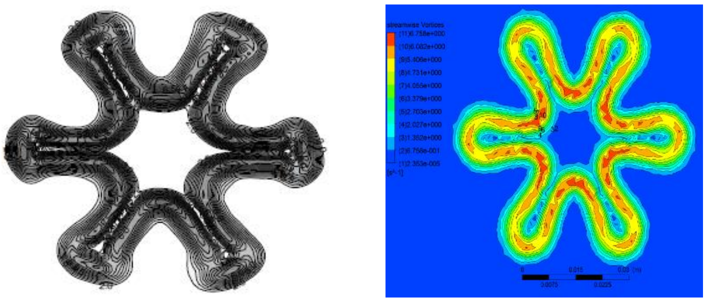


Fig.13 Normal vorticity field at 20mm in DP-SPIV and numerical model

RESULTS AND DISCUSSION:

Comprehensive analysis shows that there is no large variation in pumping performance of lobed nozzles. This shows that the pumping ratio mainly dependent on the axial velocity. Comparing the axial velocity of all nozzles it can be seen that double semicircular scalloped nozzle has high axial velocity than the other nozzles. This is because of the spoiler added to the double semicircular nozzle. The axial velocity of triangular scallop nozzle falls next to double semicircular nozzle and there is no variation in axial velocities in the remaining nozzles.

Streamwise vorticity of lobe tip scallop nozzle is higher than all nozzles. Therefore it can be seen that it has the highest mixing effectiveness than all nozzles. Double triangle scallop falls next to lobe tip scallop. This is because there is a spoiler in between the double triangular scallop nozzle. And single triangle scallop nozzle has least streamwise vorticity distribution. The presence of spoiler enhances the mixing which is absent in the single triangular scallop nozzle.

Mixing effectiveness of all nozzles is compared against each other in single graph as shown in figure 4.66. And also the total pressure recovery coefficient is compared against each other as shown in figure 4.67.

The lobe tip scallop nozzle is having highest mixing effectiveness than all other nozzles. Also mixing effectiveness rate increases rapidly until 1.5d. However there is more pressure drop in lobe tip scalloped nozzle is more. Therefore it is not considered best feasible solution. The pressure drop of double triangular scallop nozzle is within the acceptable limits and also mixing effectiveness is higher compared to other nozzles except lobe tip scallop nozzle. And mixing effectiveness of single triangular scallop nozzle is lower than all other nozzles near the end of mixing duct. Hence double triangle scallop nozzle is considered as best scalloped nozzle out of the available options. And lastly the spoiler added to double semicircular nozzle increases vorticity of flow but there is no significant improvement in the mixing effectiveness.

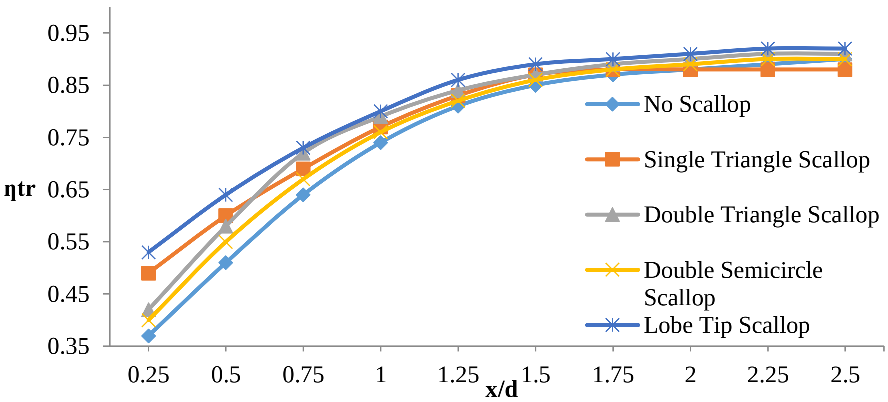


Fig.14 Mixing effectiveness of lobed nozzles along x-direction

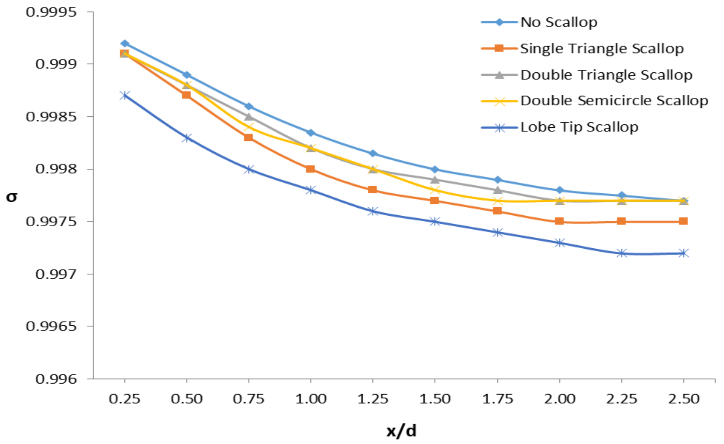


Fig.15 Total pressure recovery coefficient of nozzles along x-direction

CONCLUSION:

1) There is less variation in pumping performance between lobed nozzles with scallop.
2) Induction of lobe tip scallop in triangle scallop nozzle induces pressure loss.
3) There is no large variation in mixing effectiveness by adding spoilers like in the case of double semicircle scallop nozzle.
4) Mixing effectiveness increases rapidly until 1.25d but rate of increase slows down after 1.5d.
5) Double triangle scallop nozzle is found to have high mixing effectiveness with less pressure drop.
6) Lobe tip scallop nozzle is found to have high mixing effectiveness but at the cost of pressure drop.

Lobed nozzle mixers can be utilized in two ways one as infrared suppressor and other as noise suppressor. For present work we considered only thermal based analysis. So one can consider noise suppression as future study and also measuring infrared emissions from the scalloped nozzles due to change in temperature. Mixing efficiency plays only part in reducing the noise and infrared signature. Hence the other factors which are not considered in the present work also plays important role and can be considered for future work.

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