Numerical Optimization of converging diverging miniature cavitating nozzles

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Abstract:
The work focuses on the numerical optimization of converging diverging cavitating nozzles through nozzle dimensions and wall shape. The objective is to develop design rules for the geometry of cavitating nozzles for desired end-use. Two main aspects of nozzle design which affects the cavitation have been studied i.e. end dimensions of the geometry (i.e. angle and/or curvature of the inlet, outlet and the throat and the lengths of the converging and diverging sections) and wall curvatures (concave or convex).

Angle of convergence at the inlet was found to control the cavity growth whereas angle of divergence of the exit controls the collapse of cavity. CFD simulations were carried out for the straight line converging and diverging sections by varying converging and diverging angles to study its effect on the collapse pressure generated by the cavity. Optimized geometry configurations were obtained on the basis of maximum Cavitational Efficacy Ratio (CER) i.e. cavity collapse pressure generated for a given permanent pressure drop across the system. With increasing capabilities in machining and fabrication, it is possible to exploit the effect of wall curvature to create nozzles with further increase in the CER. Effect of wall curvature has been studied for the straight, concave and convex shapes. Curvature has been varied and effect of concave and convex wall curvatures vis-à-vis straight walls studied for fixed converging and diverging angles. It is concluded that concave converging-diverging nozzles with converging angle of 20\degree and diverging angle of 5\degree with the radius of curvature 0.03 m and 0.1530 m respectively gives maximum CER.

Preliminary experiments using optimized geometry are indicating similar trends and are currently being carried out. Refinements of the CFD technique using two phase flow simulations are planned.

Keywords: Converging-diverging nozzle, cavitation, convex, concave.

1. Introduction:
Cavitation is the formation and subsequent implosion of bubbles in a liquid. Small bubbles form when the total tension applied to the liquid is greater than a critical pressure. Upon reaching subsequently high pressures they implode catastrophically leading to a generation of high pressures and temperatures. Hydrodynamic cavitation is produced by pressure variations in a flowing liquid due to the geometry of the system. The high pressures and temperatures can be used to break chemical bonds leading to accelerated chemical reactions, wastewater treatment and material synthesis, they can also be used to abrade and clean surfaces, in creating sprays and atomization etc\textsuperscript{[2]}. Hydrodynamic cavitation offers more versatility in terms of scale-up and is reportedly more efficient than acoustic cavitation\textsuperscript{[2]}. Hydrodynamic cavitation can be created through the use of high-pressure/high-speed homogenization, orifice plates and converging-diverging nozzles. In the current study we report simulation studies on hydrodynamic cavitation in converging-diverging nozzles to arrive at design rules for creating optimal nozzle designs for various end applications.

There are three main aspects of the nozzle design that affect cavitation – (i) the end dimensions, angle and/or curvature of the inlet, outlet and the throat and the lengths of the converging $l_{\text{converging}}$ and diverging $l_{\text{diverging}}$ sections, (ii) the wall curvature in the converging and diverging sections.
diverging sections and (iii) wall roughness. Studies in literature have focused on the optimization of the lengths and dimensions of the converging-diverging nozzles with straight walls\(^2\). Theoretical studies however have focused primarily on nozzles with straight walls or have not paid attention to the aspects of wall curvature. The effect of wall curvature of the converging and diverging sections on cavitating flows has never been reported in the literature to the best of our knowledge. The curvature which can broadly be classified as straight, convex or concave (Figure 1(a), (b) & (c)) influences the nature of the pressure profiles without affecting the absolute pressure values at the outlet and the throat (Figure 2). With increasing capabilities in machining and fabrication, it is possible to exploit the effect of wall curvature to create nozzles with maximum CER. Different wall curvatures were simulated using CFD software and bulk pressure and velocity history were obtained for further estimation of bubble dynamics. In the present study Rayleigh-Plesset equation is solved till the point where compressibility of liquid can be neglected (bubble wall velocity is less than the velocity of sound in liquid) after which Tomita-Shima equation \(^3\) is used when the compressibility of liquid medium is needs to be considered (bubble wall velocity is greater than the velocity of sound in liquid).

![Figure 1: The three geometries of the converging–diverging nozzle showing the convex, concave and straight curvatures.](image)

![Figure 2: Pressure profiles along the nozzle length for the concave-concave, convex-convex and straight-straight nozzles for a constant flow rate \(l_{total}=0.02\) m, \(r_{inlet}=r_{outlet}=0.001\) m, \(r_{throat}=0.0005\) m, flowrate = 1.2 l/min).](image)

2. Geometries selected for simulation:
CFD simulations were carried out for straight line converging-diverging nozzle by varying angle of convergence and divergence from 5° to 60° to study the effect of convergence and divergence angles on CER. CER in terms of collapse pressure can be defined as the ratio of cavity collapse pressure to permanent pressure drop in the system. Configuration which gives high collapse pressure and minimum permanent pressure drop has been selected as an optimum. CER is reported as \(R_{efficiency}\) i.e. ratio of collapse pressure to permanent pressure drop. Inlet & outlet pipe diameters were taken as 0.002 m and throat diameter was taken as 0.001 m. Length of convergence and divergence were varied according to the angle of convergence and divergence (table 1).

| Angle of convergence / divergence | 5°  | 10° | 20° | 30° | 40° | 60° |
|-----------------------------------|-----|-----|-----|-----|-----|-----|
| Length of convergence / divergence (m) | 0.010 | 0.0057 | 0.0028 | 0.0018 | 0.0013 | 0.0008 |

For Convex and concave converging-diverging nozzle, radius of curvature has been varied by keeping angles of convergence and divergence constant, to study the effect of curvature on CER. For concave converging-diverging nozzles, curvature of the converging section was varied from 0.0062 m to 0.0440 m and curvature of the diverging section was varied from 0.0430 m to 0.6420 m is discussed later.
3. Simulation Strategy:
Design module available in Ansys 13 was used to construct converging-diverging nozzle geometries. 2D geometry was sufficient for converging-diverging nozzle because of the axial symmetry. The meshing used was QUAD type meshing, and the mesh number was approximately 20,000. Single phase steady state CFD simulations for the cavitational geometry are done in FLUENT 6.2. This involves solving momentum balance based on the geometry of the cavitational device, 2D axisymmetric simulations are done using Eulerian approach and k-ε realizable turbulence model was used. The simulations were carried out till the residual values dropped below $10^{-6}$. The cavity dynamics model developed by Mahulkar et. al. (2008)\textsuperscript{[1]} for finding the cavity radius, the collapse pressure and cavity inner temperature of the collapsing cavity, the maximum pressure reached inside the collapsing cavity, the nature of the cavity dynamics (transient or oscillating) has been employed in this study.

4. Boundary Conditions:
The boundary conditions used for the simulations were, velocity inlet and pressure outlet. Generally, pipe velocity is kept in the range of 2-3 m/s for non-cavitating flows in pipe. To produce cavitating condition in the system, velocity was increased and chosen in the range of 6-9 m/s. Hence, the inlet velocity in the pipe was kept as 6.37 m/s arbitrarily and the outlet pressure was kept equal to atmospheric pressure. All simulations were carried for 1 μm of initial cavity size containing 75% non-condensable gases, after initial assessment of the effect (not reported here) of cavity diameter.

5. Results and discussion:
There is a significant pressure loss in the flow though the nozzle which can be attributed to shear loss as well as cavitation loss (phase change). Pressure lost in the nozzle is used for the generation of cavities which on collapse generates significantly high pressure which can be used for end-use, such as physico-chemical changes in the cavitating liquid.

5.1 Effect of converging-diverging angle:
Effect of converging-diverging angle was studied by varying converging and diverging angle from 5° to 60° of straight line converging-diverging nozzle. It was observed that as the diverging angle increase CER decreases (Figure 4). It can be concluded from table 2 that converging angle of 20° and diverging angle 5° shows maximum ratio of collapse pressure to permanent pressure drop and can be said to be an optimum geometrical configuration in terms of highest CER.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
Diverging angle $\rightarrow$ & 5° & 10° & 20° & 30° & 40° & 60° \\
\hline
Converging angle $\downarrow$ & CER & CER & CER & CER & CER & CER \\
\hline
5° & 13056.43 & 12396.48 & 7726.77 & 4338.69 & - & - \\
10° & 1262.49 & 11471.62 & 9292.53 & 4530.85 & - & - \\
20° & 14545.05 & 12319.72 & 9956.28 & 4557.21 & - & - \\
30° & 14148.70 & 12240.97 & 10956.80 & - & - & - \\
40° & 13607.01 & 11850.38 & 7685.55 & - & - & 1831.29 \\
60° & 11968.17 & 10835.17 & 6355.46 & - & - & 1454.95 \\
\hline
\end{tabular}
\caption{cavitational efficacy ratio (CER) of straight line converging diverging nozzles.}
\end{table}

CER - Ratio of collapse pressure to permanent pressure drop.
$\cdot\cdot\cdot$ indicates that cavity growth occurs in this configuration but do not exhibits cavitation activity such as cavity collapse and generation of pressure.

5.2 Effect of curvature:
Effect of curvature was studied for the optimum converging and diverging nozzle configuration obtained earlier for the case of straight line converging-diverging simulations in the previous section by varying the radius of curvature (as defined in Figure 1(b,c)). For concave converging-diverging nozzles, curvature radius of the converging section was varied from 0.0062 m to 0.0440 m.
and curvature of the diverging section was varied from 0.0430 m to 0.6420 m. It was observed that CER in the case of concave curvature of converging-diverging nozzles is higher than straight line converging-diverging nozzles. Optimization of Concave shaped converging-diverging nozzles was done by single parameter optimization technique. Curvature radius ‘R’ of the converging section was varied from 0.0062 m to 0.0440 m by keeping the radius of the curvature of the diverging section 0.1090 m constant and optimum converging section curvature was obtained as 0.03 m (Figure 5). Curvature radius of the diverging section was varied from 0.0430 m to 0.6420 m by keeping curvature radius of the converging section to 0.03 m constant and optimum radius curvature of the diverging section was obtained as 0.1530 m (Figure 6). As convex curvature of converging-diverging nozzle shows less CER than straight line nozzles, it is not discussed in details.

6. Conclusions:
Effect of converging diverging angles and the curvature (straight, concave and convex) on the converging-diverging nozzle has been studied and optimum configuration has been reported. Concave converging-diverging nozzles with converging angle of 20° and diverging angle of 5° with the radius of curvature 0.03 m and 0.1530 m respectively gives maximum CER i.e. $1.7 \times 10^4$, 1.18 times greater than straight line. However, further refinements in the CFD techniques using two phase flow simulations are planned.

Reference:
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