Study of Cavity dynamics in a Hydrodynamic Cavitation Reactor

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***Abstract:** Cavitation is defined as sequential formation, growth and rapid collapse of micro-bubbles or cavities in liquid medium with releasing large amount of energy within small time interval (in few micro seconds). On the Basis of mode of generation, there are four types of cavitation: Hydrodynamic cavitation, Acoustic cavitation, Optic cavitation and Particle cavitation. Hydrodynamic and Acoustic cavitation occur as the result of tension prevailing in liquid while Optic and Particle cavitation occur as the result of local deposition of energy in liquid. Hydrodynamic cavitation has a great scope of scale-up on an industrial scale due to its ability in generating cavitation at a much larger scale than acoustic cavitation. To study the flow characteristics inside a Hydrodynamic cavitating device, computational fluid dynamics (CFD) software is used to simulate flow phenomena in various cavitating devices.*

This paper reports optimization of various geometrical parameter of different hydrodynamic cavitating reactor such as Slit, Circular and elliptical venturi. Different operating and geometrical parameter such as divergence angle (5.5^0, 6.5^0, 7.5^0), slit height/diameter to length ratio (1:1, 1:2, 1:3) and operating inlet pressure to the cavitating device (2, 4, 6, 8, 10 atm) were selected to study the inception, growth and dynamic of cavitation. Cavitational model and Turbulence model is used to study the CFD of cavitation reactor. In present work, the study of different geometries of venturi (like slit, circular and elliptical) shows that venturi with slit height/diameter to length ratio 1:1 and divergence angle 5.5^0 is an optimum geometry for best cavitational activity.

***Keywords:** Hydrodynamic Cavitation, Computational Fluid Dynamics (CFD), Venturi.*

1. INTRODUCTION

Cavitation is the phenomenon of sequential formation, growth and rapid collapse of micro-bubbles or cavities in liquid medium. During collapse, extremely high pressures on the order of thousands of atmospheres and extremely high temperatures on the order of thousands of degrees Kelvin are generated in the vapor phase inside the bubble. This process occurs in a few microseconds and at different locations in the reactor, thus releasing large amount of energy. Consequently, highly reactive free radicals are generated in the process due to the dissociation of vapours which enhance the rates of the chemical reaction such as oxidation. These effects are responsible for the intensification of the processes like Water and Effluent Treatment, Emulsification, Leaching, Surface cleaning, Microbial cell disruption reaction and sonochemistry etc. Saharan et al., [1, 2] have studied the application of hydrodynamic cavitation and stated that it has scope to scale up on an industrial scale for enhancement the efficiency of the waste water treatment units.

On the basis of mode of generation there are four principle type of cavitation-

Hydrodynamic Cavitation: It is produced by pressure variation in a flowing liquid caused by the velocity variation in the system by changing the flow geometry of the flow system.

Acoustic Cavitation: It is a result of pressure variation in a liquid when ultrasound (sound with frequency greater than 16 KHz) waves pass through it.

Optic Cavitation: This type of cavitation is produced as a result of the rupture of a liquid due to high-intensity light or a laser.

Particle Cavitation: It is produced by any type of elementary particle beam (e.g., a proton) rupturing a liquid, resulting in cavitation.

According to Lauterborn (1980b), hydrodynamic and acoustic cavitations are the result of tensions prevailing in a liquid, while optic and particle cavitations are the consequence of local deposition of energy. Hydrodynamic and acoustic cavitations are mostly used in process flow application involving various physical and chemical transformations. [3]

Few years back cavitation was normally known as destructive phenomena due to its detrimental effect on the hydraulic devices such as pump, propeller, nozzles etc. But in last two decades scientist have tried cavitation phenomena for carry out various chemical and physical transformations due to its ability in generating and impacting energy directly to the point where it is actually required. These effects are related to the

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size, the time-averaged shapes/cavitation bubble of the vaporized structures and their area of influence. Pumps, valves, propellers, nozzles and numerous other devices can be affected by cavitation reactor. From several years, many researchers have been obtaining experiment on dynamic of cavitation to develop the flow elements such as nozzles, orifices, and venturies. Such types of constriction is placed in a pipe carrying a stream of fluid, there will be an increase in velocity, and hence an increase in kinetic energy, at the point of constriction.

Venturi meter and orifice meter are widely used for head flow meters in the industry and also used for generating cavitation with improved design. A venturi, has advantage over the orifice due to its smooth converging and diverging sections and it can generate a higher velocity at the throat for a given pressure drop to achieve a lower cavitation number . But an orifice has an advantage that it can adapt more number of holes in a given cross sectional area of the pipe. The flow dynamics at the throat depends on the number of cavities that can be generated. In this work, we numerically analyze various designs of the cavitating reactor (Slit, Circular and elliptical venturi) by varying operating condition and geometrical parameters. CFD was used to observe the Hydrodynamic behavior inside a cavitator and to optimize the different cavitating reactors.

2. APPROACH

The approach followed in this paper is based on the assessment of selected simulation problems which are considered to be typical and represents the cavitation applications. In a general design of the cavitation reactor (venturi) of different geometries like slit, circular, elliptical which essentially consists of a converging section, a throat and a diverging section (Figure 1) and design of cavitation reactor given in table 1.

Cavitation starts with a nucleation step/ cavity inception, followed by isothermal expansion of cavity where it attains a maximum radius and reach the sufficient energy after attaining a maximum size, the cavity shrinks isothermally till a critical radius, after which the cavity shrinks adiabatically till it collapses. When a cavity grows to reach a required size, its residence time in the low pressure zone inside the throat should be optimal. Shorter residence time will not allow to grow the cavity to its required size and larger value will allow the cavity to grow and coalesce it with other cavities which decrease cavitational yield. Therefore, the ratio of the slit height/diameter to length is to be optimized for the venturi. Thus, in this paper the ratio of the slit height/diameter to its length ranging from 1:1 to 1:3 was chosen for optimization.

After attaining its required size, cavity enters the high pressure region where adiabatic collapse occur, the rate of pressure recovery is controlled by the angle of the divergent section. For adiabatic collapse the pressure recovery rate should be high, but not too high as boundary layer separation occur in the divergent region and that lead the loss of the final recovered pressure value. Thus, the angle of the divergence section is to be optimized for the venturi. So, in this paper divergence angle varied from 5.5^0 to 7.5^0 (the divergence angle of a standard non-cavitating venturi ranging from 11^0 to 15^0) for optimization.[4]

3. CFD MODEL ANALYSIS FOR CAVITATIONAL REACTOR

In the CFD (Computational Fluid Dynamics) approach, the equations that govern the process of interest are solved at discrete locations in the domain numerically in an iterative manner. CFD predicts the fluid flow, heat and mass transfer, chemical reactions and related phenomenon by solving numerically the set of governing mathematical equations. The technique is very powerful and spans a wide range of industrial and non-industrial applications. Some examples are aerodynamics of aircrafts and vehicles, hydrodynamics of ships, electrical and electronic engineering, marine engineering, chemical process engineering, biomedical engineering etc.

4. NUMERICAL METHOD

The CFD model equations are solved using the ANSYS FLUENT 14.5 as solver. In all cases, cavitating geometries are simulated in 3D axis-symmetric to see the flow domain and we have cut 2D plane along the axis of the geometries in the analysis. In that our hexahedral cells have been generated which is ranging from 1, 00, 000 to 3, 00, 000. Steady state cavitation was taken in the multiphase model with no slip velocity. In model solving density, momentum and vapour are discretized using FIRST ORDER UPWIND discretization scheme and turbulent kinetic energy and turbulent dissipation rate are discretized using SECOND ORDER UPWIND discretization scheme. The governing equations are the mass conservation and the momentum balance equations have solved using the SIMPLEC algorithm and in turbulence model standard k-ε is used.

The vapour mass fraction f is governed by equation:

$$\frac{\partial}{\partial t}(\rho_m f) + \nabla.(\rho_m v_v f) = \nabla.(\gamma \nabla f) + R_e + R_c$$

Where ρ_m =mixture density,

f =Vapour mass fraction,

γ= effective exchange coefficient,

v_v =vapor phase velocity,

R_e and R_c denote vapour generation and condensation rate which can be expressed as a function of the main flow parameters.

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When P< P_{sat} $$R_e = C_e \frac{V_{ch}}{\sigma} \rho_l \rho_v \sqrt{\frac{2(P_v - P)}{3\rho_l}}(1 - f)$$

P> P_{sat} $$R_c = C_c \frac{V_{ch}}{\sigma} \rho_l \rho_l \sqrt{\frac{2(P - P_v)}{3\rho_l}} f$$

Where V_{ch} =Characteristic velocity,

σ=surface tension coefficient,

P_v = Vapour pressure

C_e and C_c are 0.02 and 0.01 respectively.

5. RESULT AND DISCUSSION

5.1 Effect of inlet gauge pressure and Cavitation number

Cavitation consist three steps phenomena cavity inception, cavity growth and adiabatic collapse. When these cavities enter the low pressure region it will grow to a larger size and cavitational intensity will be higher at that site. This cavitational intensity depends on the inlet gauge pressure, and cavitation number.

Cavitation number is a dimensionless number used to characterize the flow condition and degree of cavitation in cavitational reactor [1].The cavitation number defined as $$C_v = \frac{P_2 - P_v}{\frac{1}{2}\rho v_0^2}$$

Where P_2 is the fully recovered downstream pressure, P_v is the vapour pressure of the liquid, v_0 is velocity at throat of cavitational reactor.

Under ideal condition cavitation number should be less than or equal to 1 for cavity generation. But cavities can also be generated at cavitation number greater than 1 due to presence of dissolved gases which acts as a pre nuclei. At lower cavitation number, higher cavitational activity obtained i.e. higher number density of cavities which results into the coalescence with each other and from cavity cloud [1]. According to Saharan et al. [1] the optimum cavitation number are ranging from 0.15 to 0.25 for the waste water treatment application.

The optimum cavitation number in our case is obtained in the range of 0.10 to 0.20 for best cavitational activity. Figure 2, 3 and 4 and table 2 shows the effect of inlet gauge pressure for different cavitational reactor. Pressure contour for elliptical increases up to 6atm and then decrease but for slit and circular increases upto 10 atm for different inlet gauge pressures. 6 atm for elliptical venturi, 10 atm for slit venturi and 8 atm for circular venturi are optimized inlet pressure for best cavitational activity.

5.2 Optimization of slit height/diameter to length ratio

This parameter decides the maximum size of cavity which can grow in pressure recovery region. Shorter the length lesser will be time spent by cavity in low pressure region. In this work slit height/diameter to length ratio was varied in the range of 1:1 to 1:3. Table no.3 shows that the velocity decreases and cavitation number increases with an increase to slit height/diameter to length ratio.[6] Pressure plot figure 5, 6 and 7 and pressure contour figure 8, 9 and 10 shows that 1:1 is optimum slit height/diameter to length ratio for optimized inlet gauge pressure to get best cavitational activity, since the length of low pressure region maximum in the case of 1:1 slit height/diameter to length ratio which allows the cavities to grow to a maximum size before collapse.

5.3 Optimization of divergence angle

The Divergence angle is an important parameter to control pressure recovery rate in divergence section. In this analysis half angle of divergence was taken ranging from 5.5^0 to 7.5^0 to see the effect. Table no.4 shows that the velocity decreases with an increase of divergence angle [6]. Pressure plot figure 11, 12 and 13 and pressure contour figure 14, 15 and 16 shows that 5.5^0 is optimum for different cavitational reactors at respective optimized inlet gauge pressure for best cavitational activity. At higher divergence angle pressure recovers faster and the length of cavitation zone is lesser and hence the cavity shrinks collapse quickly. The quicker collapse increases with the increase in the divergence angle, and decrease the cavitational zone due to faster pressure drop [6]. Pressure recovery is high due to boundary layer separation at higher divergent angle because the collapse of cavities is faster as compared to lower divergent angle. But for the small divergent angle pressure recovery will be smooth and cavities will grow to reach the maximum size before it collapse.

6. FIGURE AND TABLE

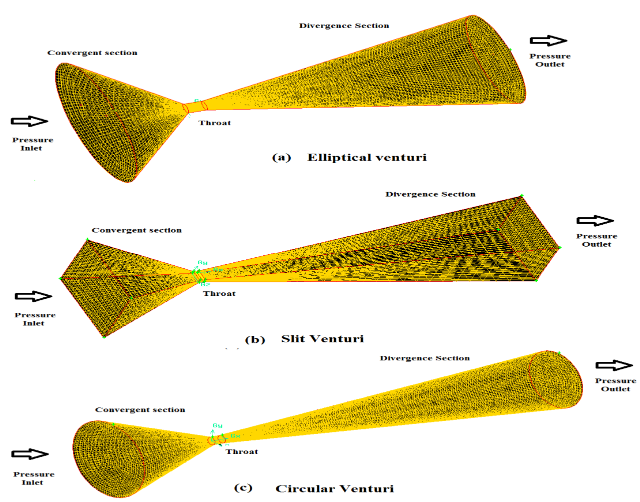

Fig. 1. Schematic and various diagram of different venturi (a) Elliptical Venturi, (b) Slit Venturi and (c) Circular Venturi.

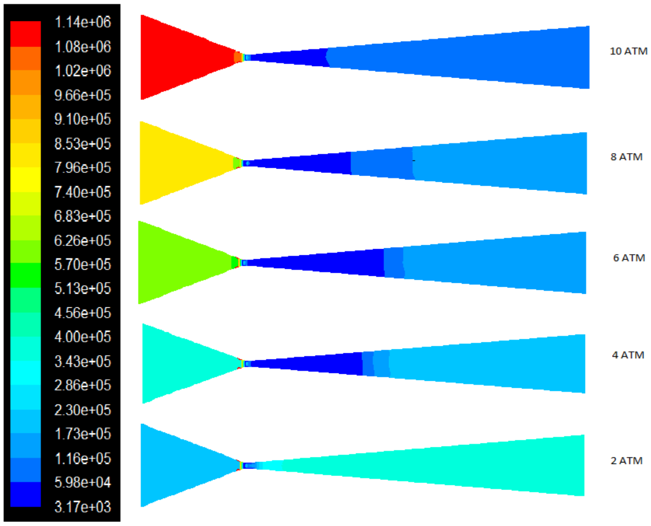

Fig. 2. Pressure contour at different gauge pressure in Elliptical Venturi

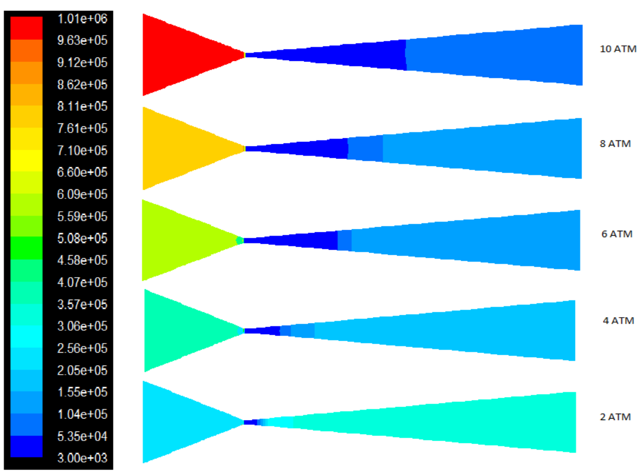

Fig. 3. Pressure contour at different gauge pressure in Slit Venturi

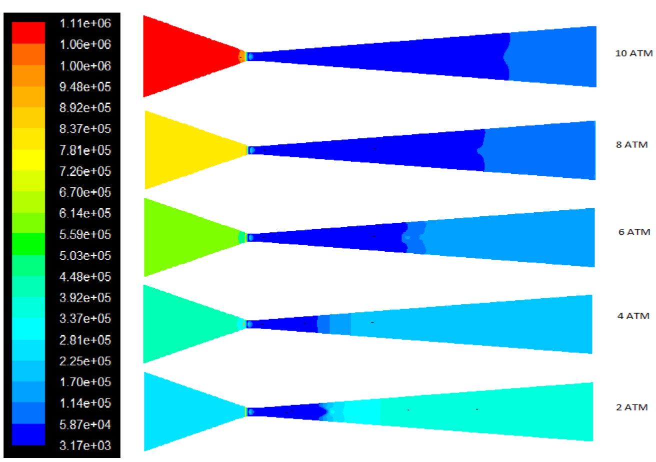

Fig. 4. Pressure contour at different gauge pressure in Circular Venturi

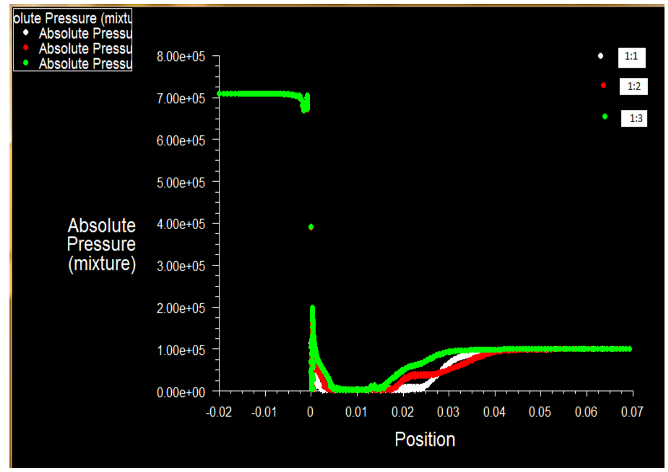

Fig. 5. Pressure plot of Elliptical Venturi for various diameter to length ratios

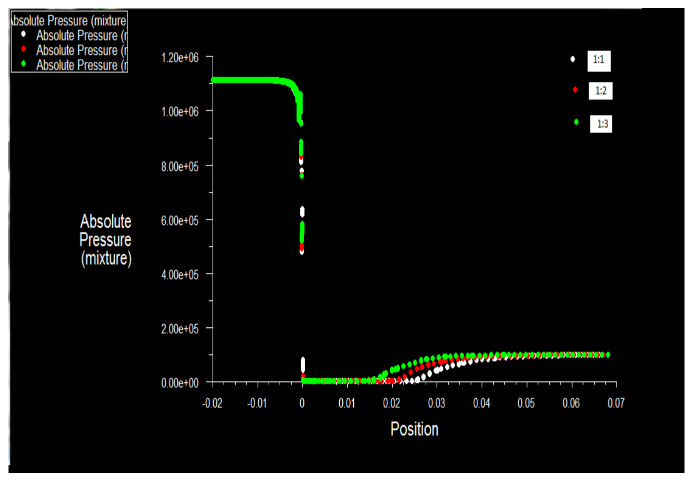

Fig. 6. Pressure plot of Slit Venturi for various height to length ratios

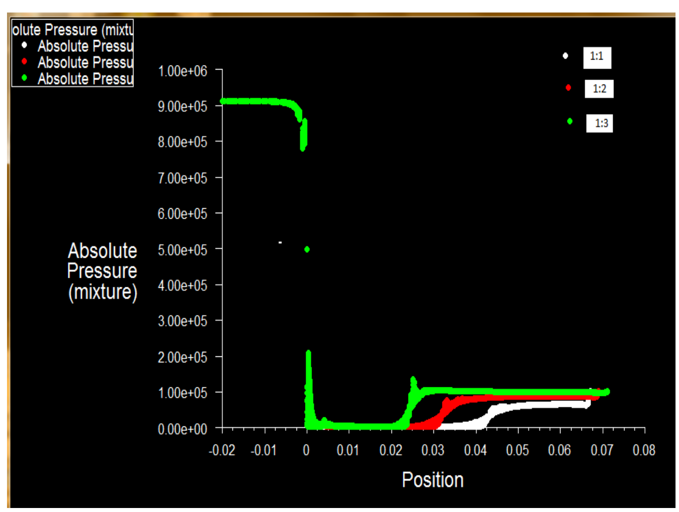

Fig. 7. Pressure plot of Circular Venturi for various slit height/diameter to length ratios

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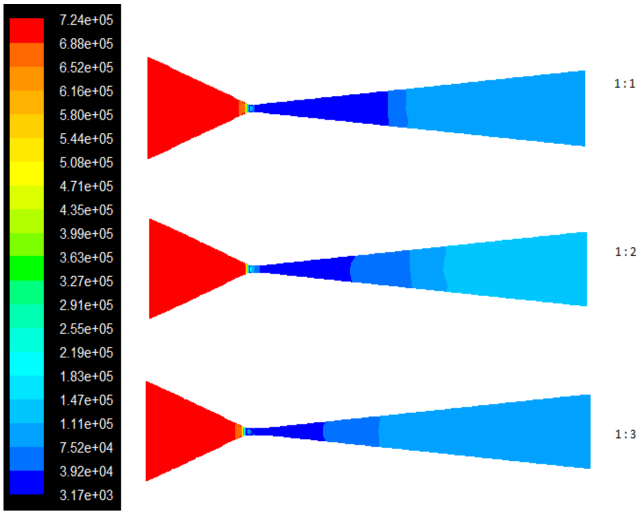

Fig. 8. Pressure contour of Elliptical Venturi for various slit height/diameter to length ratios

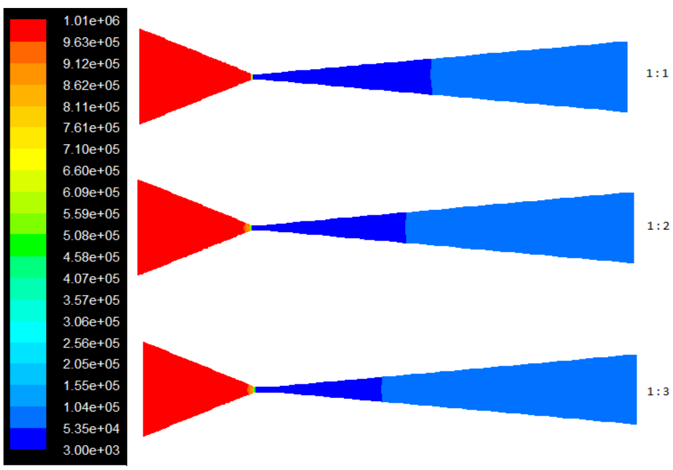

Fig. 9. Pressure contour of Slit Venturi for various slit height/diameter to length ratios

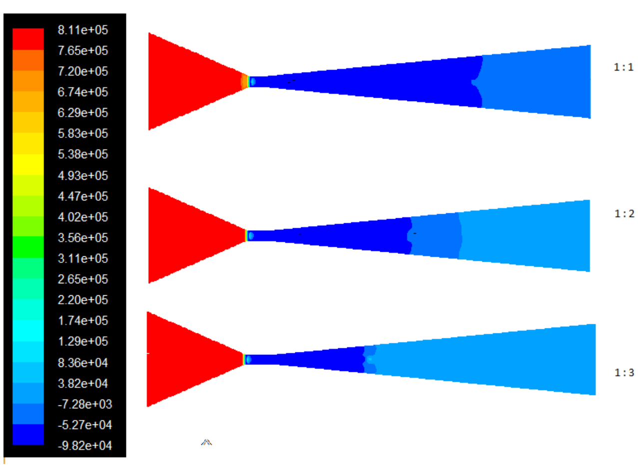

Fig. 10. Pressure contour of Circular Venturi for various slit height/diameter to length ratios

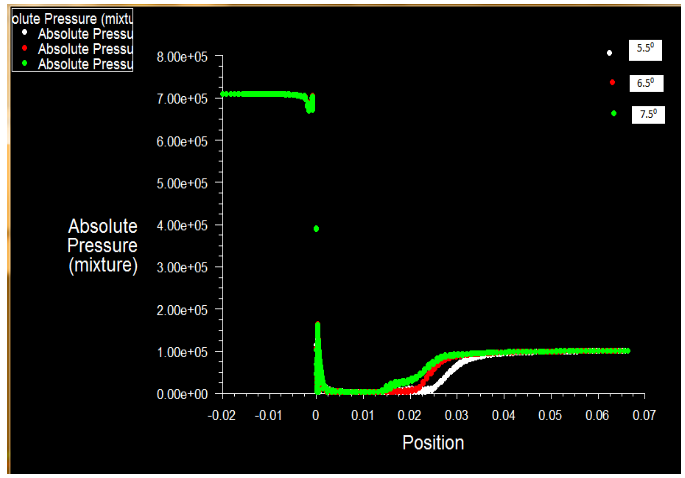

Fig. 11. Pressure plot of Elliptical Venturi for various divergence angles

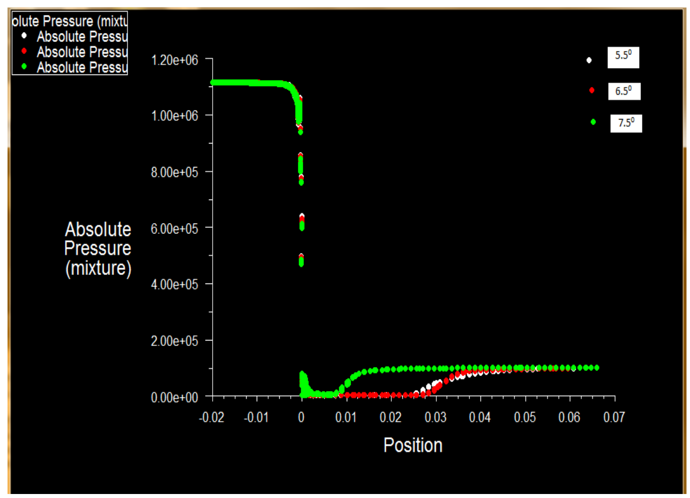

Fig. 12. Pressure plot of Slit Venturi for various divergence angles

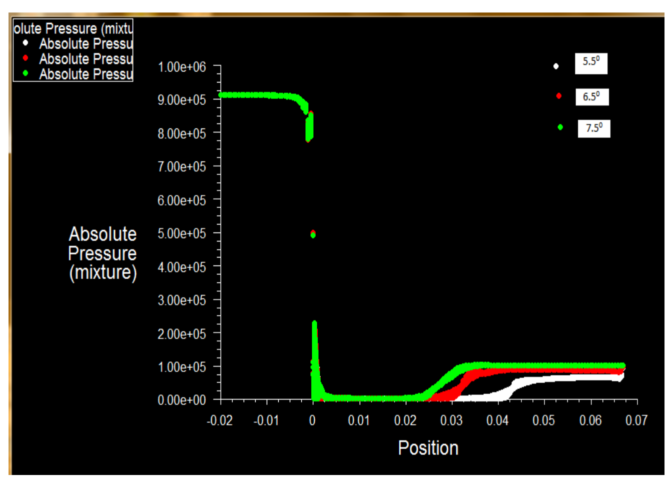

Fig. 13. Pressure plot of Circular Venturi for various divergence angles

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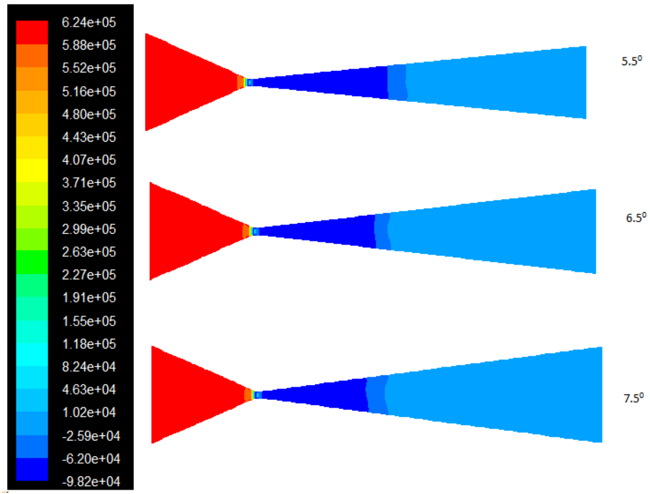

Fig. 14. Pressure contour of Elliptical Venturi for various divergence angles

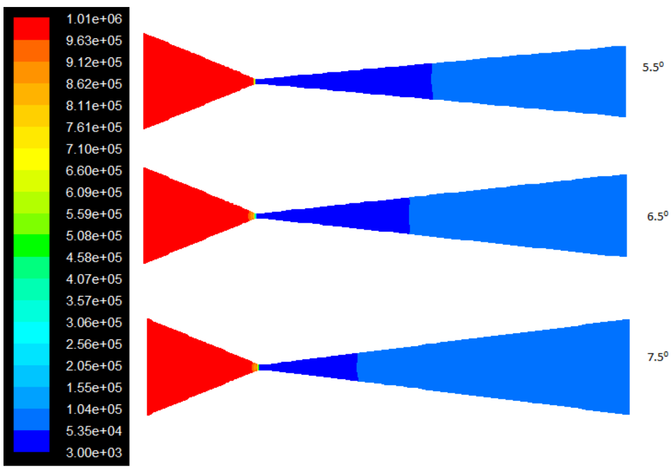

Fig. 15. Pressure contour of Slit Venturi for various divergence angles

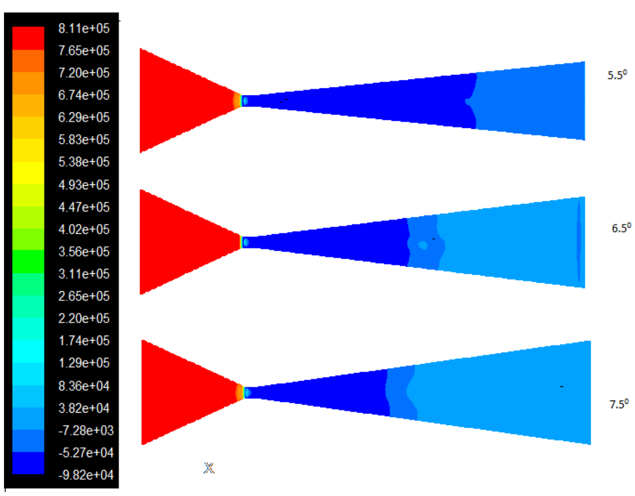

Fig. 16. Pressure contour of Circular Venturi for various divergence angles

Table 1. Geometrical Details for various cavitational reactors

Geometry	Dimensions	Throat Area
Elliptical	a=1.43; b=0.7	3.14
Slit	W=3.14; H=1	3.14
Circular	r=1	3.14

Table 2. Cavitation Number for different inlet gauge pressures for Elliptical Venturi, Slit Venturi and Circular Venturi (for 1:1 different slit height/diameter to length ratio and 5.5^0 Half Divergence Angle)

Inlet gauge pressure	Elliptical Venturi		Slit Venturi		Circular Venturi	
	Velocity (m/s)	Cavitation No.	Velocity (m/s)	Cavitation No.	Velocity (m/s)	Cavitation No.
2	21.62	0.420	21.72	0.416	21.83	0.412
4	27.89	0.253	28.11	0.248	25.21	0.247
6	32.87	0.182	33.29	0.177	33.40	0.176
8	37.81	0.137	37.77	0.138	37.89	0.137
10	40.55	0.119	41.77	0.112	41.92	0.112

Table 3. Cavitation Number for different slit height/diameter to length ratio for Elliptical Venturi (at 6 atm gauge pressure), Slit Venturi (at 10 atm gauge pressure) and Circular Venturi (at 8 atm gauge pressure)

Height /diameter to length ratio	Elliptical Venturi		Slit Venturi		Circular Venturi	
	Velocity (m/s)	Cavitation No.	Velocity (m/s)	Cavitation No.	Velocity (m/s)	Cavitation No.
1:1	32.87	0.182	41.77	0.112	37.89	0.137
1:2	32.52	0.186	41.76	0.113	37.80	0.137
1:3	32.11	0.190	41.58	0.114	37.58	0.139

Table 4. Cavitation Number for different half divergence angle for Elliptical Venturi (at 6 atm gauge pressure), Slit Venturi (at 10 atm gauge pressure) and Circular Venturi (at 8 atm gauge pressure)

Half Divergence Angle	Elliptical venturi		Slit Venturi		Circular Venturi	
	Velocity (m/s)	Cavitation No.	Velocity (m/s)	Cavitation No.	Velocity (m/s)	Cavitation No.
5.5^0	32.87	0.182	41.77	0.112	37.89	0.137
6.5^0	32.77	0.183	41.67	0.113	37.80	0.137
7.5^0	32.55	0.185	41.31	0.115	37.59	0.139

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7. CONCLUSION

The flow through different hydrodynamic cavitating reactors (elliptical, circular and rectangular venturis) was numerically simulated with water by taking steady flow condition in turbulent k-ε scheme. It has been found that different geometries of cavitating reactor have different pressure plot and contour at same pressure drop. The optimization of venturi was carried by taking three important parameters divergence angle, slit height/diameter to length ratio and inlet pressure.

The divergence angle affects the intensity of collapse of active cavities by controlling pressure recovery rate at cavitational zone. By increasing angle of divergence, the cavitational zone is decreasing but intensity of collapse of active cavities is increasing. It is seen that the optimum divergence angle for maximum cavitational activity is 5.5^0 for elliptical, circular and rectangular venturis out of studied angles from 5.5^0 to 7.5^0.

The slit height/diameter to length control the residence time of the cavity in the low pressure region and its intensity of collapse. With increasing the ratio, the length of cavitational zone got decreases at constant pressure drop. It is seen that the best ratio for maximum cavitatinal zone is 1:1 for elliptical, circular and rectangular venturies out of studied ratios form 1:1 to 1:3.

The inlet gauge pressure which gave the optimal cavitational zone ranging from 0.1 to 0.2, was obtained 6 atm inlet gauge pressure for elliptical venturi, 10 atm inlet gauge pressure for slit venturi, and 8 atm inlet gauge pressure for circular venturi.

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