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CFD Analysis and Optimization of Circular and Slit Venturi for Cavitational Activity

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Abstract: **This study presents the three-dimensional analysis and optimization of the two types of venturimeter, viz. Circular Venturi and Slit Venturi on the basis of the various geometrical parameters using Computational Fluid Dynamics. Cavitation is the phenomena of formation, growth and subsequent collapse of micro bubbles/cavities when the pressure falls below the vapor pressure of the fluid and then subsequent increase of the pressure in the downstream section. Cavitation has a wide range of application in chemical processes, biomedical and cleaning purposes. The geometry as well as operating parameters (pressure and cavitation number) plays an important role for the maximum cavitational effect in Hydrodynamic cavitation.**

The optimization was done for different parameters viz, inlet pressure, height to length ratio and half divergent angle, which affect the cavity formation in the throat, residence time of cavity and pressure recovery zone in the divergent section of the Venturi. The CFD study was carried out for Circular Venturi as well as Slit Venturi with varying operating and geometrical parameters. Based on the CFD study conducted in this work and experimental data obtained from the literature, it was concluded that the Circular Venturi at 5 atm gauge inlet pressure and throat diameter to length ratio of 1:1 and divergence angle of 6.5 degree gives the maximum cavitational yield in terms of higher cavity collapse pressure, longer cavity life and higher intensity. Similarly for Slit Venturi, 8 atm gauge inlet pressure, slit height to length ratio of 1:1 and divergence angle of 5.5 degree are the optimized parameters for maximum cavitational activity.

1. INTRODUCTION

Hydrodynamic Cavitation can be defined as the process of vapor formation, growth and sudden collapse due to decrease in the pressure at the throat and/or vena contracta and subsequent increase in pressure in the downstream section of a venturi or orifice plate. Formation of cavities occurs only when the pressure around throat/vena contracta of constriction falls below the vapor pressure of liquid generating high energy cavities/bubbles. These cavitation bubbles then further undergo expansion and compression and finally collapses and thus resulting in high energy density with high pressure and temperature at the location of cavity collapse. The radicals thus generated have high oxidation potential and can undergo dissociation reaction due to their capability in initiating various chain reactions and oxidizing organic compounds. Due to high turbulence it ameliorates the heat and mass transfer coefficient. The hydrodynamic cavitation has various applications such as degradation of organic pollutants, water disinfection, emulsification, nano-particle synthesis, extraction, leaching, etc. Saharan et al., [1,2] have studied the degradation of various organic pollutants using hydrodynamic cavitation and stated that hydrodynamic cavitation has scope of scale up on an industrial scale for the efficiency enhancement of the conventional treatment unit. Similarly the hydrodynamic cavitation has also been tested for the various other processes involving physical destruction phenomena such as leaching, surface cleaning and water disinfection [3, 4].

Hydrodynamic Cavitation can be achieved by flow through a duct with constriction by an orifice plate or by constricted convergent-divergent passage. Cavities are formed at the constriction where the pressure falls below the vapor pressure due to increase in kinetic energy. Subsequently cavities grow and enter the pressure recovery zone which results in collapse of cavities and release of energy. Orifice and Venturi both are used as cavitational reactor where orifice has an advantage that it can accommodate more number of holes and hence high perimeter to open area ratio with high cavitational activity Moholkar et al., (1999) [5].

In Venturi with low Cavitation number, due to gradual convergent and divergent passage, the cavity formation starts at throat so as to get high velocity with high pressure recovery rate. The work presents the modified designs of both Circular Venturi and Slit Venturi where study has been carried out with varying operation conditions and geometrical parameters. The two important operating conditions i.e. inlet pressure and cavitation number affects the cavitational intensity and length of cavitational zone. The geometrical parameters i.e. Height to length ratio and divergent angle affect the size of cavity and control the rate of collapse of cavity. The two types of Venturi designed were optimized to get the maximum cavitation. CFD analysis was done to observe the behavior of cavity formation and collapse inside the Cavitational Reactor.

2. DESIGN OF CAVITATIONAL REACTOR

A modified cavitational reactor was used where the liquid flow through a convergent section then through throat where the cavity forms and finally through a divergent section where the cavity grows and collapses. The two type of venturimeter i.e. Circular Venturi and Slit Venturi (see Figure 1) where the throat is of different shape were analyzed with different operating conditions and geometrical parameter. The diameter in case of Circular Venturi is 2mm whereas, height and width of throat in Slit Venturi were 2mm and 3.14mm respectively. The length of upstream section and downstream section were 20mm and 65mm respectively. Cross-section area of throat was kept constant for both cases.

Cavitation is the phenomena where the cavity formation, cavity growth and cavity collapse take place which is dependent on operating conditions and geometrical parameter such as height to length ratio of throat and divergent angle of the downstream section.

Inlet pressure is the main operating condition for the optimization as it affects many applications. The pressure was varied to obtain optimum value and avoid super-cavitation. Thus the inlet pressure was varied from 1 atm to 10 atm to get maximum cavitational yield.

The efficacy to generate the cavities and quantum of cavities being generated depends on the throat size. The life of the cavity depends on the throat length and divergent angle. The higher inlet pressure increases the throat velocity and hence the cavitation number also increases which results into the increased number of cavities. Shorter the residence time, smaller will be the cavity zone but for high residence time and larger cavitation number it may form the cloud where the micro-bubbles club together to form bigger bubbles. For optimum cavity residence time the throat height to length ratio was varied from 1:0.5 to 1:3. And hence it is taken as one important geometrical parameter for optimization.

When the cavity has grown and reaches the downstream section, intensity of the collapse of the cavity depends on the pressure recovery rate. The pressure recovery should be high enough for the cavity to collapse but not too high forming boundary layer separation in the divergent section. Hence for the present study the divergence angle was varied from 11° to 17° of the divergence section (half divergence angle varying from 5.5° to 8.5°).

For the optimization of both Slit Venturi and Circular Venturi CFD is used where the pressure was varied from 1 to 10 atm and geometrical parameter viz. height to length ratio of throat and divergence angle of the downstream section from 1:0.5 to 1:3 and 11° to 17° respectively, were altered to get the maximum cavitational yield in terms of higher cavity collapse pressure, longer cavity life and higher intensity.

CFD Modelling

When the liquid is subjected to decrease in pressure, which is below the saturation pressure small micro bubbles may form which under decreasing pressure get transformed into cavities and released energy on collapse. Hydrodynamic cavitation is computationally solved in the commercial software FLUENT 6.3.26 with the help of Full Cavitation model. In multiphase cavitation modeling, a basic two-phase cavitation model consists of the conventional viscous flow equations governing the transport of mixture (Mixture model) and a standard turbulence model (k-□ model).

The following vapor transport equation governs the liquid vapor mass transfer.

$$\frac{\partial(\alpha\rho_v)}{\partial t} + \nabla.(\alpha\rho_v\bar{V}_v) = R_e - R_c$$

Where,

α = vapour volume fraction

ρ_v = vapour density

$\bar{V}_v$ = vapur phase velocity

R_e, R_c = mass transfer source terms connected to the growth and collapse of the vapor bubbles respectively

The transport equation which governs the vapor mass fraction (*f*):

$$\frac{\partial(f_v\rho)}{\partial t} + \nabla.(f_v\rho\bar{V}_v) = \nabla.(\Gamma\nabla f_v) + R_e - R_c$$

Where,

f_v = vapour mass fraction

ρ = mixturedensity

$\bar{V}_v$ = vapor phase velocity

Γ = diffusion coefficient

Here R_e and R_c denote the mass transfer between the liquid and the vapor phases ie vapor generation and collapse rate in the cavitational activity. In FLUENT these values are based on Rayleigh-Plesset Equation which describes the growth of each vapor in the phenomena.

When $P<P_{sat}$

$$R_e = C_e \frac{\sqrt{k}}{\sigma}\rho_v\rho_l\left[\frac{2}{3}\frac{P_v - P}{\rho_l}\right]^{1/2}(1-f)$$

When $P>P_{sat}$

$$R_c = C_c \frac{\sqrt{k}}{\sigma} \rho_l \rho_l \left[\frac{2}{3} \frac{P_v - P}{\rho_l} \right]^{1/2} f$$

The value of constants C_e and C_c are 0.02 and 0.01 respectively. In this model, the liquid-vapor mixture is assumed to be compressible. Also, the effects of turbulence have been taken into account.

3. BOUNDARY CONDITIONS

The three dimensional geometries, see Figure 1, of both Circular and Slit Venturi were created in GAMBIT 2.2. CFD simulation was done in FLUENT 6.3.26 in 3D space with the mixture model which was used for multiphase flow. There was no slip condition, this is due to large difference in density of vapor and liquid which do not produces different velocity of both the phases. In boundary conditions the inlet pressure was varied and then with optimum inlet pressure boundary condition the other geometrical parameter were optimized. Inlet Pressure and Outlet pressure condition was defined for the nozzles. The absolute outlet pressure was taken as 1 atm. Initially with no cavity the vapor phase fraction was mentioned zero, Since the non-condensable gases has been taken into account, dissolved gas fraction was mentioned as 5 ppm which is equivalent to that present in water. The Pressure discretization scheme was LINEAR and Pressure Velocity Coupling scheme was taken as SIMPLEC. FIRST ORDER UPWIND scheme was taken for momentum and density as this may diverge the solution whereas SECOND ORDER UPWIND scheme was taken for Turbulent Kinetic Energy and Turbulent Dissipation Rate for better accuracy.

4. RESULT AND DISCUSSION

5.1 Effect of Inlet Pressure and Cavitation Number.

The number of cavity forming in the cavitational reactor and the cavitational zone intensity is largely dependent on operating condition viz. pressure gauge at inlet/upstream section and the cavitation number associated with the flow. Figure 2 and 7 shows the pressure contour for Circular Venturi and Slit Venturi at different pressure gauge at inlet side.

Cavitation number (C_v) is the dimensionless quantity which is important factor which is used to characterize the flow condition. It account for the difference between the energy head of liquid at outlet and inlet. Mathematically, it is defines as:

$$C_v = \frac{2(p_2 - p_v)}{\rho V_{throat}^2}$$

Where p_2 is the discharge pressure of bulk fluid, p_v is the vapor pressure of fluid, ρ is the density of fluid and V_{throat} is velocity of fluid at throat. The value of C_v should not be greater than 1, for the cavitation to occur. When the value of C_v is less than 1, it means the fluid energy is used to form vapors. Hence lower the cavitation number greater will be the cavitational activity but not too low so that the micro-bubbles form may come together and forms cavity cloud at high inlet pressure as described in the experimental study done by Saharn et al [1].

In case of Circular Venturi and Slit Venturi, (see figure 3 and 5) the pressure profile at the centerline of Venturi, where cavitational zone increases with the pressure gauge at inlet side but for the optimal condition as describe in the work of Senthilkumar et al [9], the value of cavitation number should be in the range of 0.15 to 0.25 along with critical pressure which avoids super-cavitation. Table 1 shows the variation of cavitation number on inlet pressure for both the Venturi. It was founded that velocity of the fluid increases with the inlet pressure and subsequent decrease in the cavitation number. The cavity formation also increases with the increase in the discharge pressure at the inlet side as describe by Yan and Thorpe [8]. As observed the cavity inception was very low when the discharge pressure was at lower side i.e. lower than 5 atm, till this point the cavity collapse occur as soon as the generation of cavity and higher pressure the cavity are formed and the cavitational zone cover the downstream section of Venturi and cavity cloud may form at high pressure. The optimum inlet pressure was found with the cavitation number in the range of 0.15- 0.25 for both the types of Venturi was 5 atm and 8 atm for Circular Venturi and Slit Venturi respectively.

5.2 Effect of Height to Length ratio of throat

The geometrical parameters play the important role to get the maximum cavitation yield. These can be area of throat to its perimeter ratio studied by Bashir et al [7] for different types of Venturi, height to length ratio of throat and divergence angle of downstream section. In this work height to length ratio of throat was varied for 1:0.5 to 1:3 for both the Venturi with gauge inlet pressure of 5 atm in case of Circular Venturi and 8 atm in case of Slit Venturi.

After cavity inception, the growth and collapse intensity of cavity depends on the residence time of the cavity in the throat. This is largely dependent on the geometrical parameter i.e. throat height to length ratio. The larger the length greater is the residence time of cavity. As the velocity remains constant with increasing the ratio (see Table 2), this parameter is optimized on the basis on volume of cavitational activity in the reactor. Figure 3 and 8 shows that the maximum zone for lower pressure in the Circular Venturi and Slit Venturi is given when the ratio of height to length is 1:1.

5.3 Effect of Divergence angle of downstream section

The pressure recovery rate in the Venturi is controlled by the divergence angle of the downstream section. For each of the

Venturi, study was done for different divergence angle varied from 11° to 17°. The different half divergence angle taken for analysis were 5.5°, 6.5°, 7.5° and 8.5° for both the Venturi with gauge inlet pressure of 5 atm in case of Circular Venturi and 8 atm in case of Slit Venturi. The pressure recovery rate is controlled by the divergence angle of the downstream section. Greater the divergence angle higher the pressure recovery and lesser the cavitational zone as the cavity shrinks quickly. According to the work done by Bashir et al [7] the collapse intensity also increases with the increase in the divergence angle, this is due to greater pressure drop but the cavitational activity zone decreases. In case of smaller divergent angle pressure recovers smoothly and hence cavity grows to a maximum size before collapse.

Whereas in the case of higher divergent angle, due to boundary layer separation pressure recovers immediately in the downstream section which causes collapse of cavities faster as compared to lower divergent angle. Hence for higher divergent angle the life of cavity reduces which may reduce the cavitational intensity/yields. Figure 5 and 10 represents the pressure contour at various divergence angle and Figure 6 and 11 shows the plot of pressure profile at centerline of Circular Venturi and Slit Venturi. Hence, in case of Circular Venturi the maximum cavitational activity is obtained with half divergence angle of 6.5°, whereas in Slit Venturi the optimum cavitation is shown by 5.5° (see figure 6 and 11).

5. CONCLUSION

The geometry included for CFD analysis were Circular and Slit Venturi. The inlet gauge pressure which gave the optimal cavitational zone and has the cavitation number in the range of 0.15 to 0.25 was obtained 5 atm gauge pressure at inlet side for Circular Venturi and 8 atm for Slit Venturi. The throat height to length ratio controls the residence time of the cavity in the reactor and hence the intensity of the collapse of cavity. On increasing the ratio, cavitational zone got decreased at constant pressure drop. Therefore the optimum parameter of throat height to length ratio for Circular Venturi and Slit Venturi is 1:1 for both the type. The divergence angle controls the pressure recovery rate of cavity, which regulates the size of cavitational zone. It is shown that the optimum divergence angle for maximum cavitational activity is 6.5 degree in Circular Venturi and 5.5 degree in Slit Venturi.

Hence, it was concluded that the Circular Venturi having throat of diameter of 2mm which operates at 5 atm gauge inlet pressure and throat diameter to length ratio of 1:1 and divergence angle of 6.5 degree gives the maximum cavitational yield in terms of higher cavity collapse pressure, longer cavity life and higher intensity. Similarly for Slit Venturi with slit of dimension 2mm height 3.14 mm depth operating at 8 atm gauge inlet pressure, slit height to length ratio of 1:1 and divergence angle of 5.5 degree are the optimized parameters for maximum cavitational activity.

6. FIGURES AND TABLES

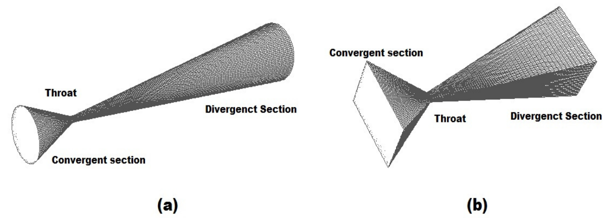

Fig. 1. Schematic diagram of (a) Circular Venturi and (b) Slit Venturi

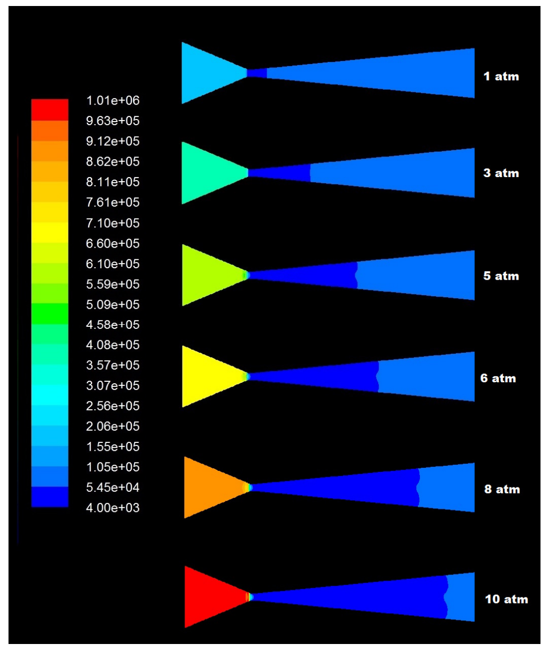

Fig. 2. Pressure contour at different gauge pressure in Circular Venturi

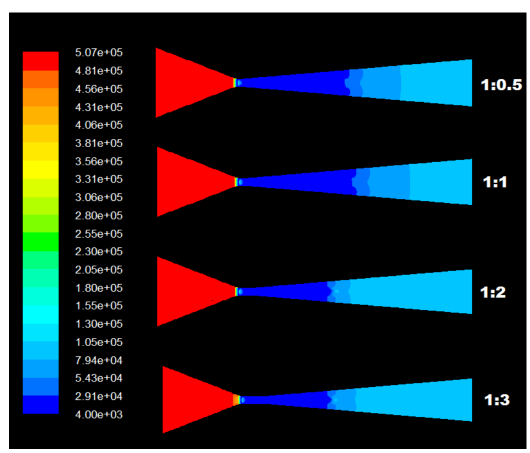

Fig. 3. Pressure contour for different throat height to length ratio in Circular Venturi

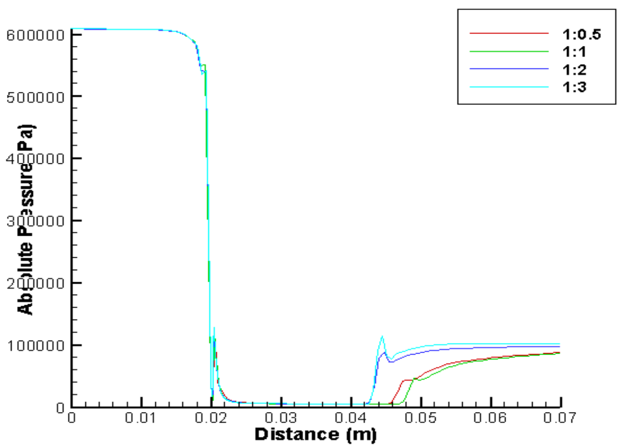

Fig. 4. Pressure plot at the center line different slit height to length ratio in Circular Venturi

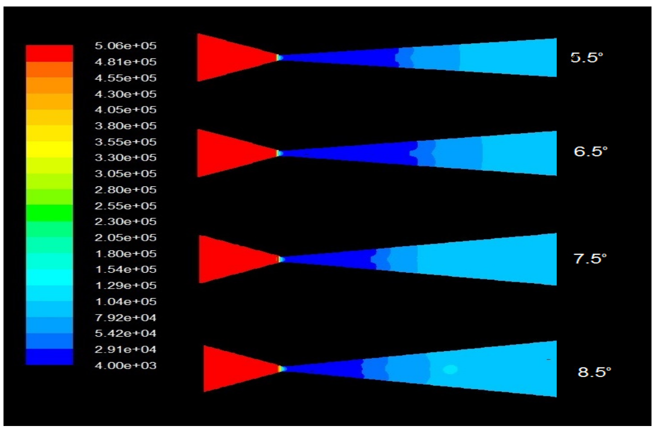

Fig. 5. Pressure contour for various half divergence angle in Circular Venturi

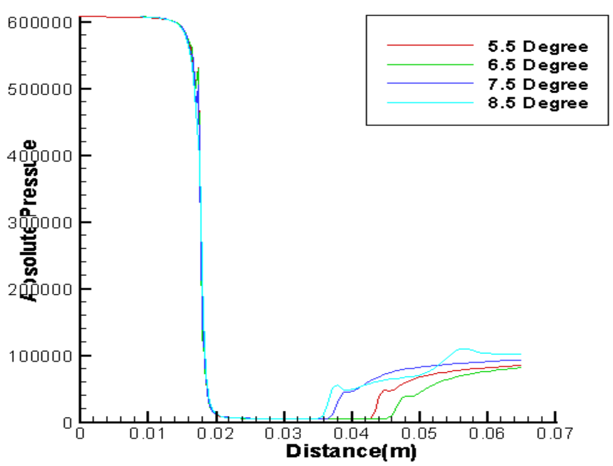

Fig. 6. Pressure plot at the center line of Circular Venturi with different divergence angle

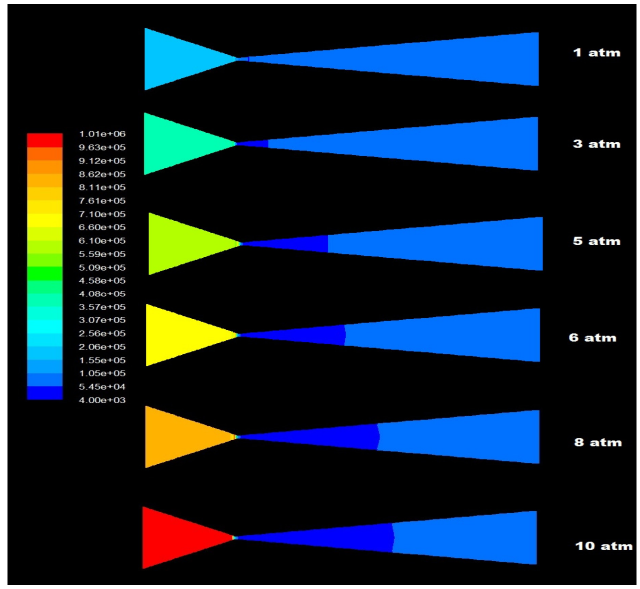

Fig. 7. Pressure contour at different gauge pressure in Slit Venturi

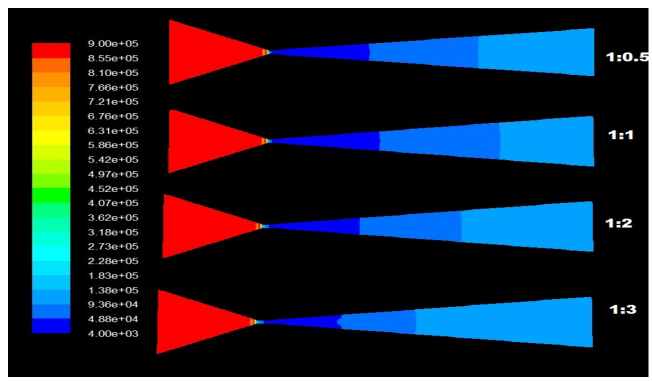

Fig. 8. Pressure contour for different slit height to length ratio in Slit Venturi

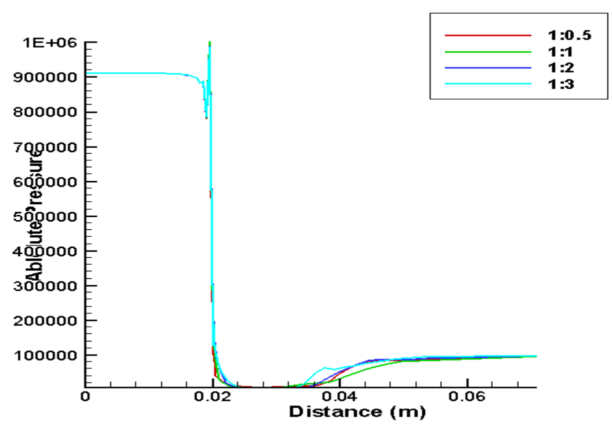

Fig. 9. Pressure plot at the center line different slit height to length ratio in Slit Venturi

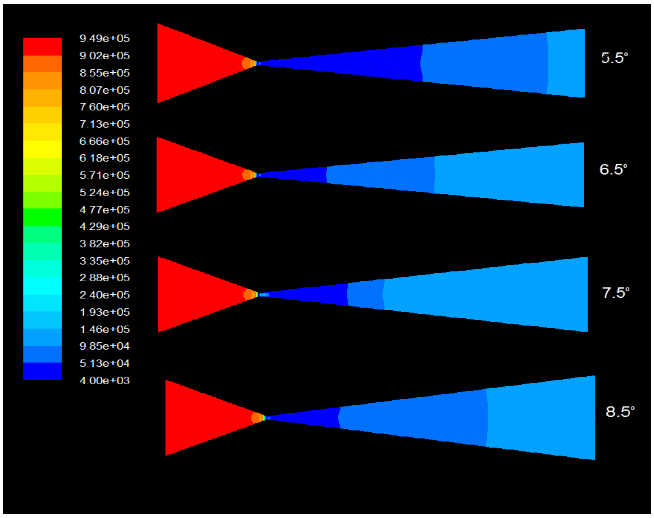

Fig. 10. Pressure contour for various half divergence angle in in Slit Venturi

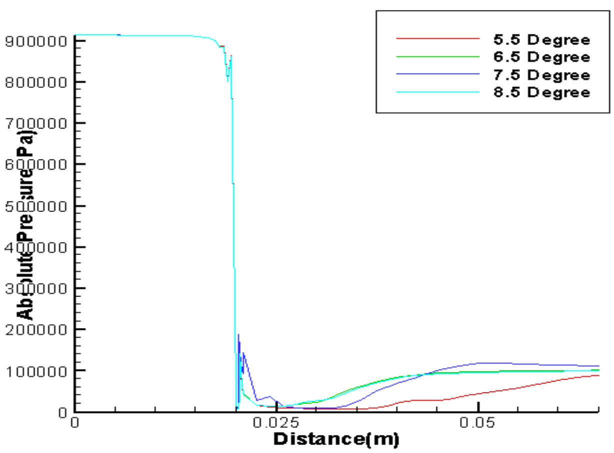

Fig. 11. Pressure plot at the center line at different divergence angle in in Slit Venturi

Table 1. Cavitation Number for different inlet pressure for Circular Venturi and Slit Venturi

Inlet Pressure	Circular Venturi		Slit Venturi	
	Velocity (m/s)	Cavitation No.	Velocity (m/s)	Cavitation No.
1 atm	16.79	0.69	9.85	2.01
3 atm	23.92	0.34	20.03	0.48
5 atm	29.09	0.23	24.74	0.31
6 atm	32.00	0.19	26.66	0.25
8 atm	36.02	0.15	30.35	0.21
10 atm	40.27	0.12	44.43	0.10

Table 2. Cavitation Number for different height to length ratio of throat for Circular Venturi (Pressure drop: 5 atm) and Slit Venturi (Pressure drop: 8 atm)

Height to Length Ratio	Circular Venturi		Slit Venturi	
	Velocity (m/s)	Cavitation No.	Velocity (m/s)	Cavitation No.
1:0.5	30.11	0.21	30.80	0.20
1:1	30.35	0.21	30.35	0.21
1:2	30.45	0.20	29.65	0.22
1:3	30.62	0.20	28.03	0.24

Table 3. Cavitation Number for different half divergence angle of downstream section for Circular Venturi (Pressure drop: 5 atm) and Slit Venturi (Pressure drop: 8 atm)

Half Divergence angle	Circular Venturi		Slit Venturi	
	Velocity (m/s)	Cavitation No.	Velocity (m/s)	Cavitation No.
5.5°	29.05	0.23	30.35	0.21
6.5°	29.10	0.23	30.27	0.21
7.5°	29.96	0.21	35.27	0.15
8.5°	33.08	0.17	37.45	0.13

(*All the contour are at the mid vertical plane of Venturi)

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