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Article

Effect of modification in flow distributor valve geometry on the pressure drop and chamber pressures, in numerical and analytical way, in ORBIT Motor HST unit

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Abstract: In this paper, an attempt has been made to analyze the effect of spool port/ groove geometry on the pressure drop and chamber pressures which effect the performance parameters of the flow distributor valve. The work mainly involves formulation of detailed mathematical model of the valve and compare them on the same platform. For mathematical modelling, Matlab has been used. The size of the orifices is considered same throughout the model for better comparison. Initially the construction and functioning of flow distributor valve along with working principles of hydrostatic motor (Rotary Piston) is shown. Next shown the analytical analysis of area change and pressure drops due to different geometry of the spool valve ports. After that the computational fluid dynamics (CFD) analysis has been shown. A complete mathematical model to describe such flow distributor valve is developed after having a comprehensive knowledge of orifice characteristics, flow interactions based on valve geometry. Equations of flow through different orifices (fixed and variable area) of the valve have been developed based on the relationships obtained earlier.

Keywords: Pintle type rotary spool valve; Flow distributor valve; Computational fluid dynamics (CFD); Orbit Motor.

1. Introduction

Rotary Piston Machines (Orbit motors/ Gerotors) are in the category of positive displacement machines which are similar to the rotor dynamic machines in construction because of the presence of rotating member (star/ rotor) and its envelope (ring/ stator). There are two basic types of rotary piston hydrostatic units. One is the fixed axis (Gerotor) unit in which kidney port type valve is used. The other one is floating axis type orbital rotor (Orbit) unit in which the pintle type or commutator type port valve is used. Although these valves are widely used in various types of hydrostatic units, but no theoretical guidelines are available in the open literature regarding their design specifications (i.e. their port sequence, geometry, positions etc.) particularly for ROPIMAs operations. In orbit motor, pressurized fluid is forced into a chamber, it causes the inner member rotate about its own axis and revolve around the stator centre. As the angular position of the inner member changes with respect to a chamber as it is being filled with fluid, at a certain angle (depending upon the design parameters) the adjacent chamber begins to fill with pressurized fluid. Once a chamber reaches its maximum volume, the fluid inside this chamber is forcing the rotor to change the chamber position. The pressure on the inner member and by entering the pressurized fluid to the adjacent chamber causes the continue rotation of the rotor.

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R Maiti [1] carried out an extensive experimental analysis to improve the performances of LSHT hydraulic motor by lead and lag of the distributor valve timing. It was noticed that torque efficiency was different due to the torsional deflection of the shaft in which the valve is embedded. Gamez-Montero and Codina [2] has evaluated the flow characteristic of a trochoidal-gear pump analytically and experimentally to understand the performance of a trochoidal-gear pump. Again Gamez-Montero and Codina [3] estimated the leakage, instantaneous flow, the flow ripple experimentally. Marko Simic, Mihael Debevec and Niko Herakovic [4] have designed valve with different metering edges of the spool and to quickly check through simulation how the valve influences the characteristics of a practical hydraulic system using analytical or CFD simulation packages.

In the present work pintle type spool valve, which is one type of flow distributor valve, is used to supply the fluid to the expansion and compression chambers of the hydrostatic motor/ pump. The inlet-outlet port sequence of the flow distributor valve is determined from the duration of phases (i.e. expansion and compression) of chambers in terms of input/ output shaft rotation for a single cylinder as well as multi-cylinder units. Very few amount of work has been done on the geometric features of the flow distributor valve and regarding that the information's are also rare in open literature.

Various performance parameters like flow, pressure, speed, and torque affect the overall efficiency of rotary piston machine. Out of these, this study is focused on the characteristics of the flow phenomenon in "flow distributor valve (pintle type rotary spool valve)" within the ambit of theoretical study and numerical analysis. The behavior of fluid flow through valve passages has been studied with accuracy considering actual operating conditions with the help of CFD simulation technique. The main objective of the present investigation is to analyze the effect of different spool groove geometries on the pressure drop, chamber pressures and pressure distribution along the fluid flow passage of an epitrochoid generated rotor stator hydrostatic unit (Orbit Motor).

The pintle valve used in hydrostatic units has a unique design [5]. The valve is integral with the output (same as rotary motion of inner member/ star) shaft. Opposite to the output end, the shaft is hollow and houses inner side of one end of gear coupling type cardon shaft. The other end of the cardon shaft is coupled to the inner member i.e. 'star'. Thus the rotation of the inner member about its own axis is transmitted to the output shaft.

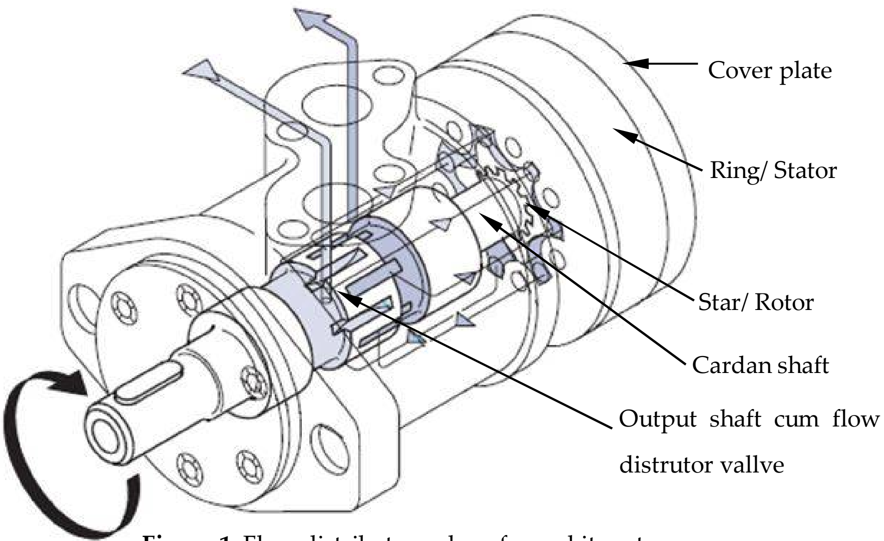

Figure 1. Flow distributor valve of an orbit motor.

On the valve body there are two circumferential grooves which are aligned to two port holes for inlet and outlet flows, in the housing. Between these two grooves there are eqispaced grooves, equal to the twice the number of lobes of star member(in present analysis twelve in numbers), in transverse direction. Each alternate transverse grooves connect to a common circumferential groove of the valve and this common circumferential groove again aligned to portholes (seven in numbers) in housing connected to the chambers. The uniqueness in the valve design is such that the set of

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transverse grooves connecting the inlet will be connected to the chambers in expansion mode and the other set connecting to the outlet will connect the chambers in compression mode. The intermediate grooves will remain disconnected. These sequences can be realized from Figure 1.

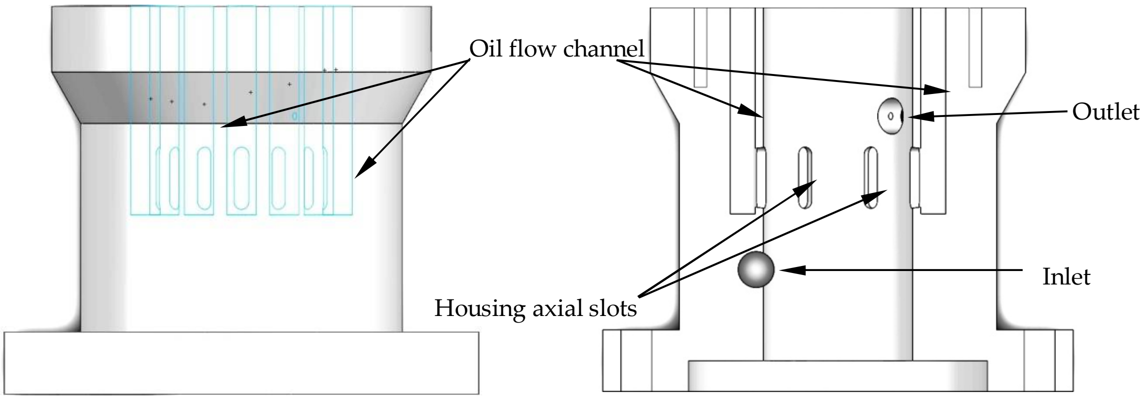

Figure 2. **H**ighlighting pathways to chamber top and sectional view of OMR 80 (danfoss) hydrostatic motor.

The housing of the OMR 80 (Danfoss) motor has seven pathways (cylindrical). These pathways can be seen in Figure 2, which shows the top and sectional view of housing and also shows the location of the spool valve, inlet flow channel, and outlet flow channel. The cross sectional view

Table 1. Tech. specifications of flow distributor valve.

Type	
Spool Port Length (mm)	18.10
Spool Port span(width) (mm)	4.80
Kdney hole length (mm)	21.30
Kidney hole width (mm)	5.10
Spool Valve Dia (mm)	42.246
Output Shaft Dia (mm)	25
No. of spool Ports	12
No. of Kidney holes	7
Spool port inclination with shaft axis (degree)	2

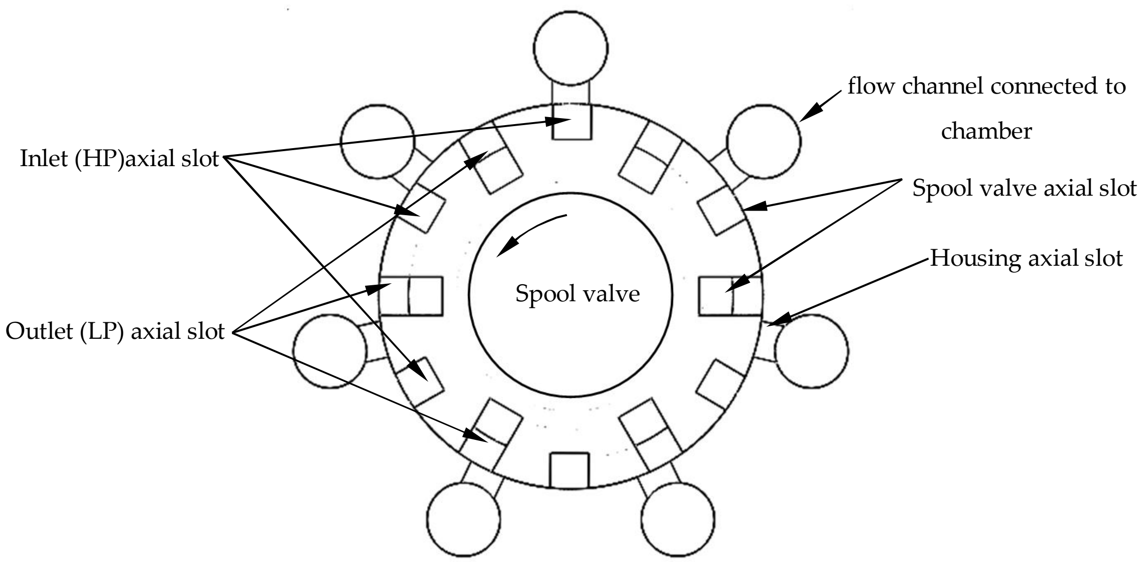

Figure 3. Sequence of flow in flow distributor valve.

of the spool valve axial slots, housing axial slots, flow channel in housing are shown here in Figure 2.The technical specifications of flow distributor valve of the orbit motor (OMR-80) is shown in table 1. The sequence of flow in flow distributor valve is shown in Figure 3.

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2. Geometric Modeling of Flow Distributor Valve

The main focus is the geometric modeling of flow distributor valve (shown in Figure 4) and the valve opening area for different angular position of the main shaft. Solid Works software is used for this geometric modeling. The rotary motion of hydrostatic motor (OMR 80) results a direct and rotary spool movement of the flow distributor valve which in turn modulates the flow of fluid through the port of the valve. The orifices of the flow distributor valve are formed by the matching between the square wave shaped convex lands on the spool and rectangular (kidney type) holes on the sleeve (i.e. motor housing).

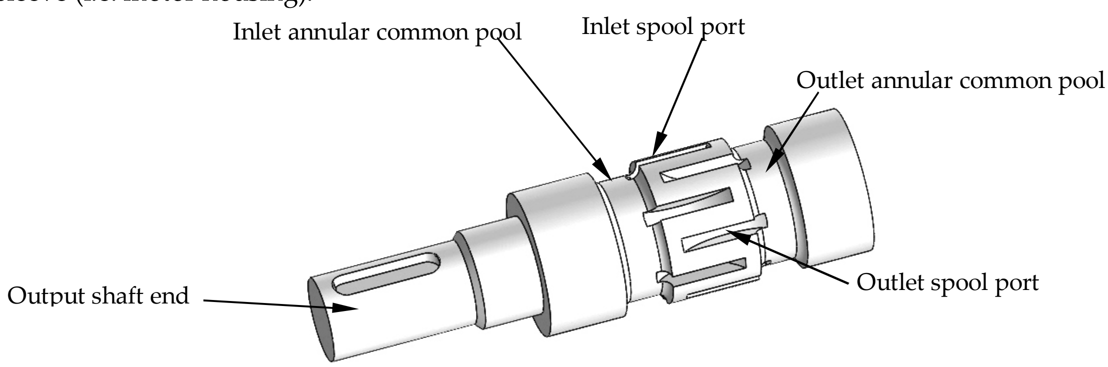

Figure 4. Flow distributor valve/spool valve geometric model.

3. Variation of Flow Distributor Spool Valve Opening Area with Output Shaft Rotation

3.1. For 2 Degree of Index Angle geometric modeling

The effective orifice areas are determined by the rotational speed (ω) of the spool. If the spool rotation angle from neutral position is denoted by θ and index angle as φ then the orifice area can be calculated as :

$$A_1 = \frac{L}{2} \times L \times \tan(\phi) \quad (1)$$

$$A_2 = A_1 + L \times (w - L \times \tan\phi) \quad (2)$$

$$A_3 = A_2 + \frac{L}{2} \times L \times \tan(\phi) \quad (3)$$

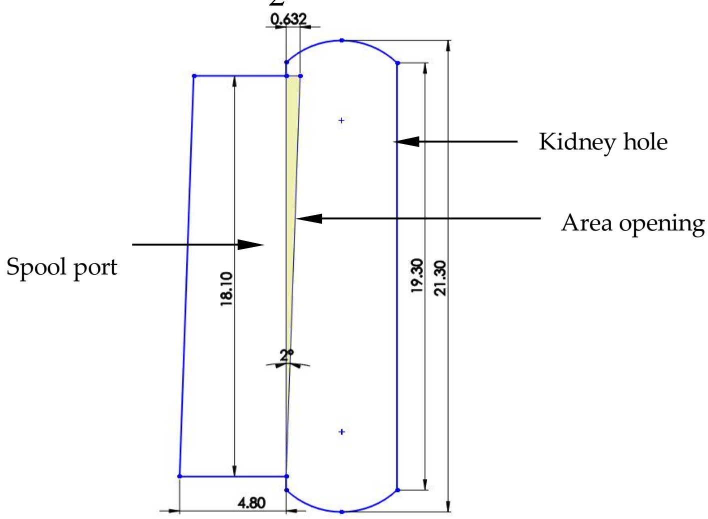

Figure 5. Initial opening area at 1st. stage.

In Figure 5 shows the initial displacement of opening (where x = radius of shaft (r) x angle of rotation (θ) x180/π) and as the shaft rotation takes place, the spool valve start opening of its axial slots into

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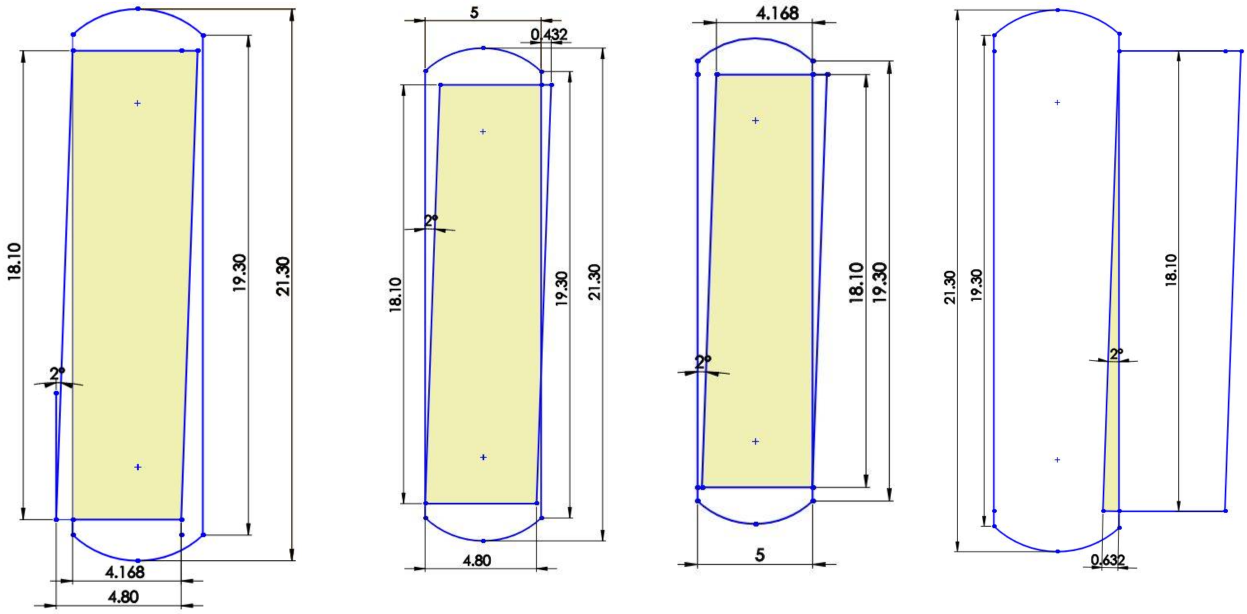
the kidney port. The variable orifice area is defined as the function of port area opened due to the overlap of the kidney port and the spool valve axial slots. The angle of rotation of the distributor valve shaft is taken as zero degree at the beginning of the valve port opening. The area variation of a single spool port opening are shown in 2-D solid works model as shown in Figure 6 below. For better understanding valve opening taken as linear travel (rotational travel of the valve has been converted into a linear scale in mm). Certain assumptions are considered for this analysis; these are as follows:

(i) Opening of a single spool valve port is considered at a time.

(ii) The hydrostatic motor chamber is at the beginning of an expansion phases in which fluid is supplied at a specific pressure from the port.



(i) Opening area 2nd. stage (ii) opening area maximum at 3rd. stage (iii) Opening area reducing stage at 4th. stage (iv) minimum area at 5th. stage

Figure 6. Spool valve port opening sequences with angular orientation.

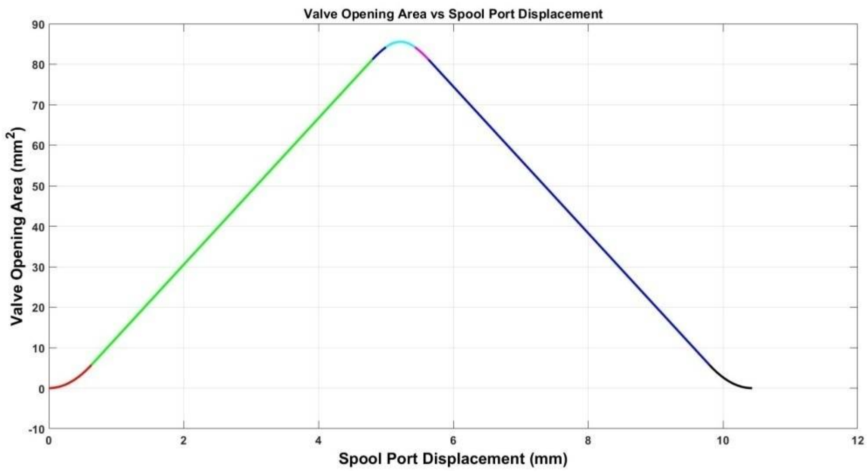


Figure 7. Valve opening area vs output shaft rotation.

3.1.1. For 2 Degree Index Angle Variation of Valve Opening Area and Pressure Drop with Distributor Valve Shaft Rotation

At initial phase of opening of the axial groove with kidney port, the triangular portion is opened due to which area opening changes parabolic with the shaft rotation. At this phase of opening maximum

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pressure drop takes place. As the further displacement of the shaft takes place the graph (shown in Figure 7) becomes linear, and then again parabolic at the maximum opening of kidney port [4, 6].

3.1.2. Mathematical modeling

The basic equation developed to represent steady-state fluid flow is the Bernoulli equation which assumes that total mechanical energy is conserved for steady, incompressible, inviscid, isothermal flow. Bernoulli's equation for pressure drop at the orifice is given as:

$$\text{Flow rate (Q)}= C_d \times A_o \times \sqrt{\frac{2\times\Delta P}{\rho}} \tag{4}$$

So pressure drop is given as:

$$\Delta P = \left(\frac{Q^2}{2\times C_d^{\,2}\times A_o^{\,2}}\right)\times\rho \tag{5}$$

Now let supply pressure = P_s

Then the respective chamber pressure $P = P_s$ - Pr. Drop

$$\text{So, } P = P_s - \left(\frac{Q^2}{2\times C_d^{\,2}\times A_o^{\,2}}\right)\times\rho$$

where,

Q = Flow rate (m^3/sec)

A_0 = Opening area of orifice (m^2)

ΔP = Pressure drop at the orifice (Pa)

C_d = Coefficient of discharge (0.995)

ρ = Density of fluid (880 kg/m^3)

It can also be shown that for a particular flow rate of fluid flow the graph for varying the opening area with pressure drop shown below in Figure 8.

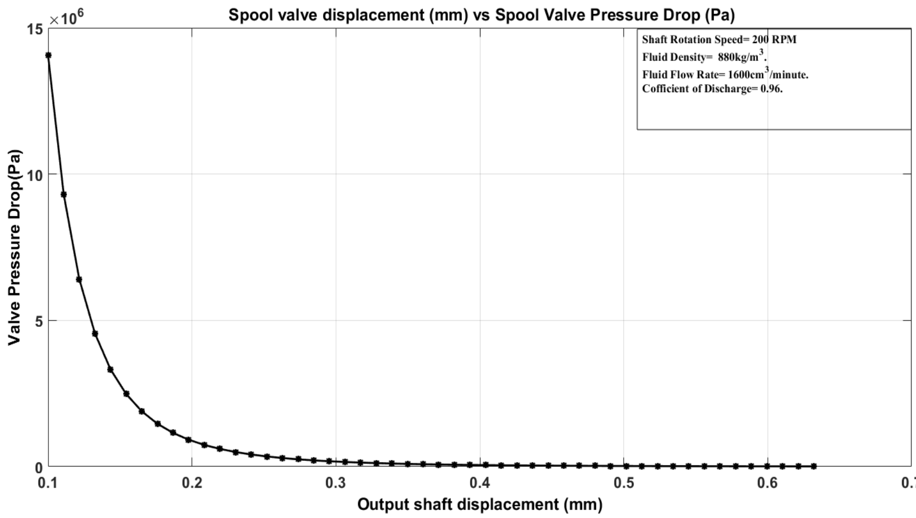

Figure 8. Spool port displacement vs valve pressure drop.

Due to the symmetric design of the flow distributor valve the area opening is also symmetric for all the 7 kidney ports of the hydrostatic unit. Area variation of each spool port is having a phase angle of 8.5714 degrees. Considering the clockwise rotation of the output shaft from the cover plate end, after every phase gap of 2π/N(N-1) degrees one of the spool port starts opening i.e. after every 8.57 degrees of rotation (for N=7) next port starts opening and fluid pressure is being applied into the orbit motor chamber to apply torque. In this manner after every 8.57 degrees of output shaft rotation, the next port starts opening by overlapping of spool port groove area with the kidney port, situated inside the body of housing, to start the fluid flow from the flow distributor valve inlet channel to the respective chambers of the orbit motor/hydrostatic unit. The 2–D plot using MATLAB

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is shown in Figure 9 below for all 7 kidney ports of the hydrostatic unit. It is observed from the plot that rate of change of area opening for all spool ports/grooves is symmetric and has a constant phase difference.

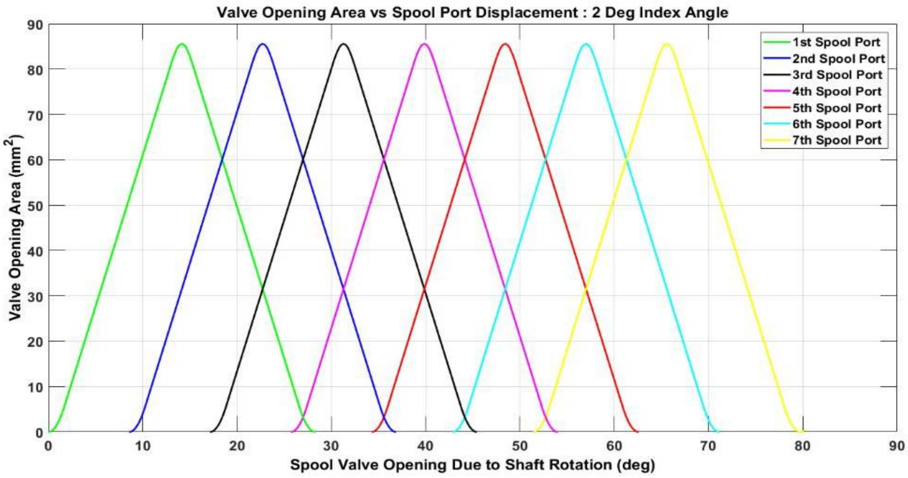
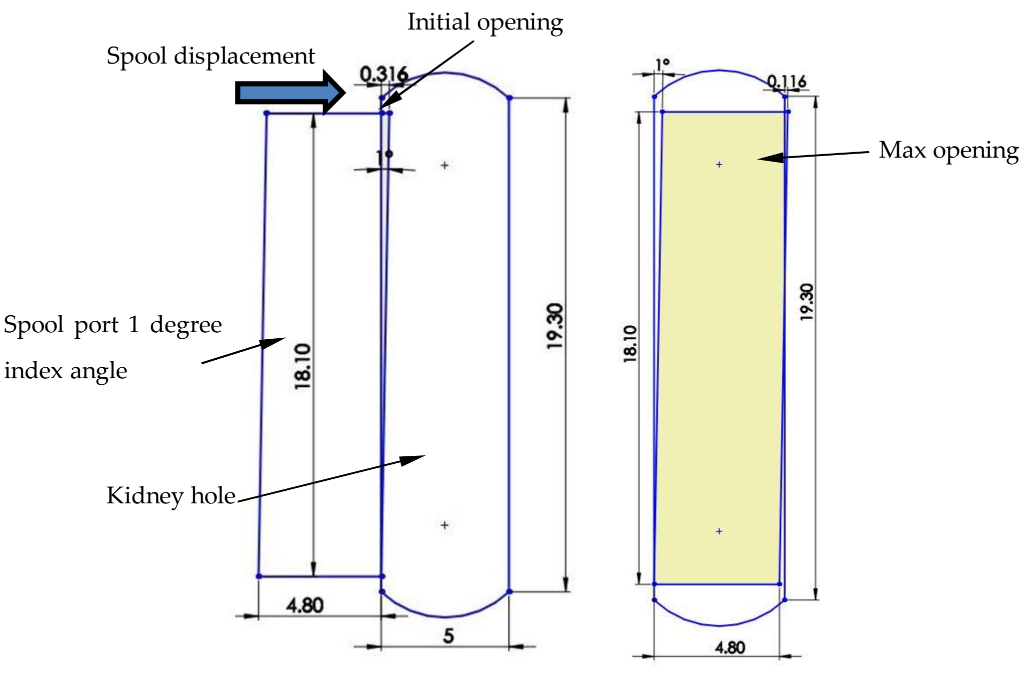


Figure 9. Spool opening area change vs shaft rotation for 2 deg. Index angle.

3.2. For 1 Degree of Index Angle of Spool Valve/Port



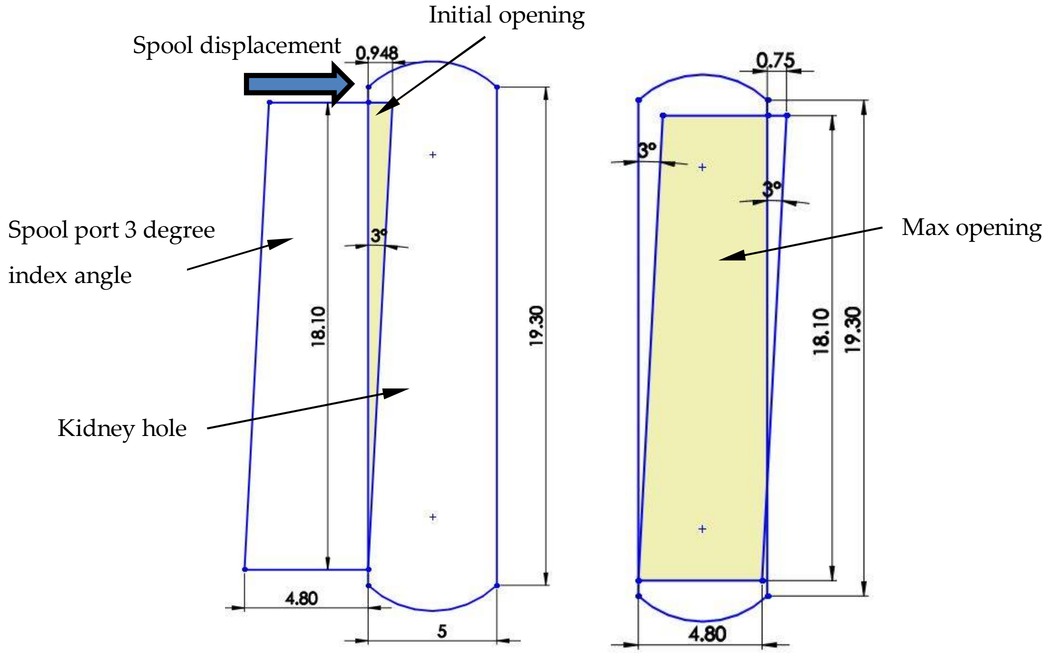
(a) Start of opening hole (b) Full open position

Figure 10. Spool port opening 2-D view.

A small local pressure drop is preferred to minimize the ripple effect and cavitations risk. The optimization of an orifice geometry involves the investigation the effect of its geometry on the pressure drop, flow rate and flow ripples. Any unfavorable behavior may degrade the performance of the hydrostatic motor/pump. Figure 10 shows the interaction of spool valve port with the kidney port of the hydrostatic motor for 1 degree of spool valve index angle.

3.3. For 3 Degree of Index Angle of Spool Valve/Port

Figure 11 shows the interaction of spool valve port with the kidney port of the hydrostatic motor for 3 degree of spool valve index angle.

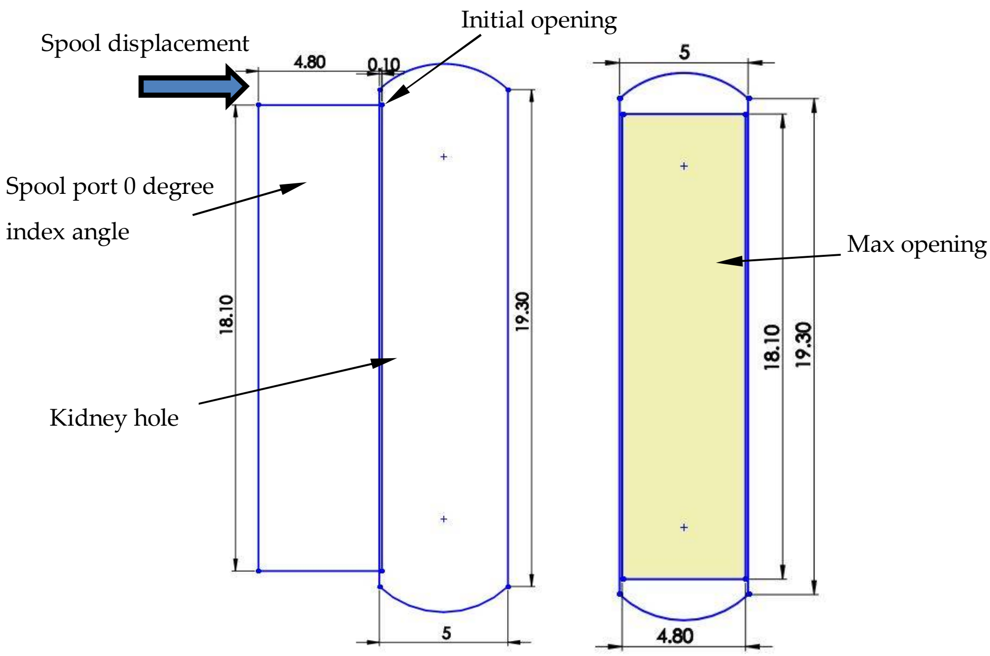


(a) Start of opening hole (b) Full open position

Figure 11. Spool port opening 2- D view for 3 deg.

3.4. For 0 Degree of Index Angle of Spool Valve/Port

Figure 12 shows the interaction of spool valve port with the kidney port of the hydrostatic motor for 3 degree of spool valve index angle.



(a) Start of opening hole (b) Full open position

Figure 12. Spool port opening 2-D view for 0 deg.

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4. Area Variations for Different Geometries of spool valve

Though the kidney ports are equispaced in the stator housing, but valve opening with increased index angle changes the rate of change of area with respect to spool shaft rotation as shown in Figure 13. The spool with higher index angle has more smooth area change curve which in turn give a smooth pressure distribution inside the flow channel of the motor.

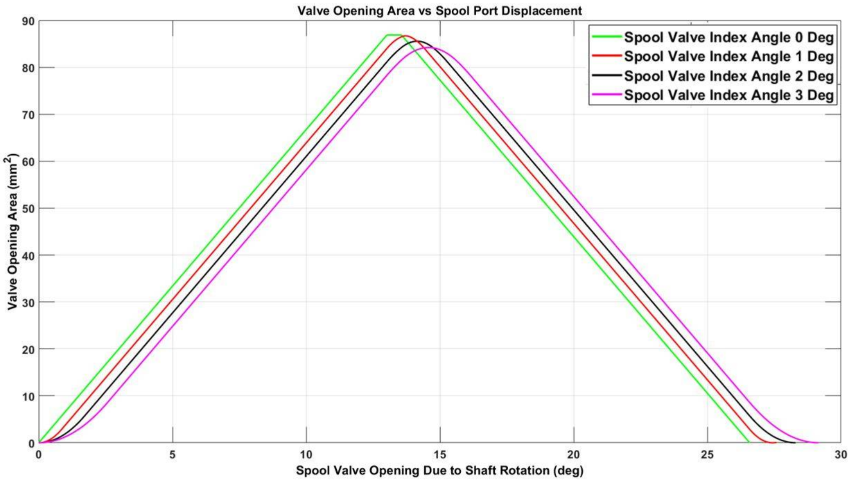

Figure 13. Spool valve opening due to shaft rotation vs opening area

5. Pressure Drop and Chamber pressure

(i) Detail study of spool valve groove openings is carried out for different geometries to analyze the local pressure drops at the opening of spool groove and the kidney hole. As the orifice opening takes place, so pressure drop takes place at the local region inside the kidney port. It is observed from the plots that for all seven kidney holes the pressure drop curve is same due to the symmetric design of the distributor valve. There is a phase difference of 8.5714 degrees between two consecutive pressure drops.

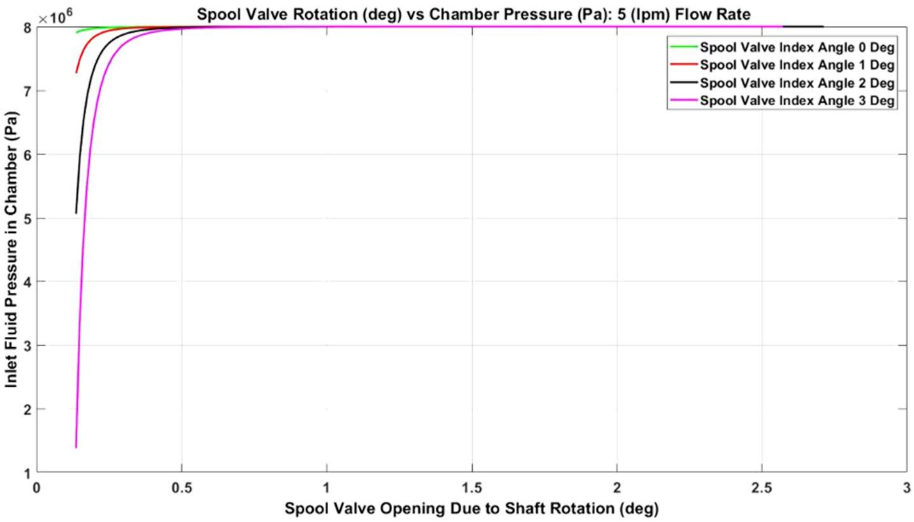

Figure 14. At 5 lpm flow rate, chamber pressure due to spool valve opening and change in valve index angle (in Deg.)

(ii) By using different geometry (change in the index angle of the groove) of the spool valve, it can be shown that the improvement in pressure drop characteristics of the flow distributor valve (pintle type) is possible. For a fixed flow rate, the pressure drop is regulated more smoothly by increasing the index angle of the spool groove from zero degree to 3 degrees. In this analysis four

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different geometric designs of the spool valve are considered for detailed study. The pressure drop variation is shown in Figure 14 for fluid flow rate of 5 lpm.

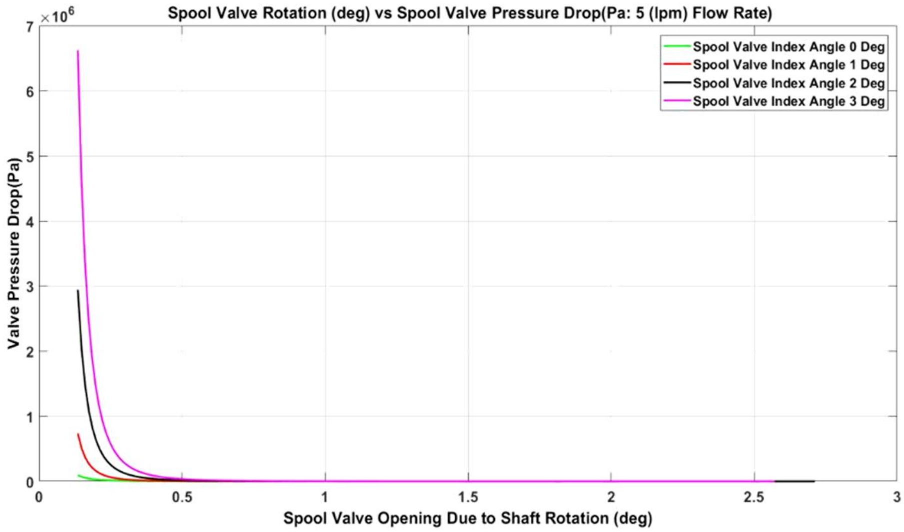

Figure 15. At 5 lpm flow rate, pressure drop due to spool valve opening and change in valve index angle (in Deg.)

(iii) As the objective is to attain optimum valve geometry without compromising the performance of the hydrostatic motor. It is observed from the analysis that for different geometries of the spool groove at constant flow rate (5 lpm), means spool groove with higher index angle gives much more smooth and regularized pressure drop curve, which in turn smoothens the pressure ripples applied into the chambers of the hydrostatic motor chambers, shown in Figure 15. Thus more continuous and gradual pressure applied reduces the pressure ripples and thus erratic operation of the motor is avoided. In this way these hydrostatic units can be used for more precision and highly sophisticated operations.

6. CFD (Fluent) Analysis

To analyze the fluid flow through the “flow passage of stator housing”, ANSYS/Fluent software is used. To do the CFD analysis, firstly develop the 3-D model of the flow channel for different angular opening of kidney port using solid works software. After developing different flow channel models, simulation has been done using CFD technique in Fluent® environment.

6.1. Analysis of Fluid Flow through “Flow Passage of Stator Housing”

By importing the solid model of fluid flow channel in fluent module of ANSYS software, a 3-D meshed model (Figure 16) with variable fineness is developed using these parameters stated in table 2 below. For this SOLID186 element has been chosen, which is a higher order 3-D 20-nodes (each node has three degree of freedom) solid element that exhibits quadratic displacement behavior. It also has mixed formulation capability for simulating fluid flow of incompressible fluids. In this analysis computational fluid dynamics (CFD) FLUENT is used to investigate the effect of groove geometry and its sizes on the flow properties for a single groove at the flow distributor valve of the hydrostatic unit. After analyzing, the streamline velocities and pressure distributions in the groove region and the flow path up to the chambers for various geometric designs of the spool groove are obtained. For square shaped spool groove the streamline velocities and leakages are highly affected.

Streamlines can give a qualitative idea about the flow of fluid through the fluid passage, if any irregularities of flow exist, in that case, where they develop and what influences they have on the hydrodynamic performance of the flow distributor valve.

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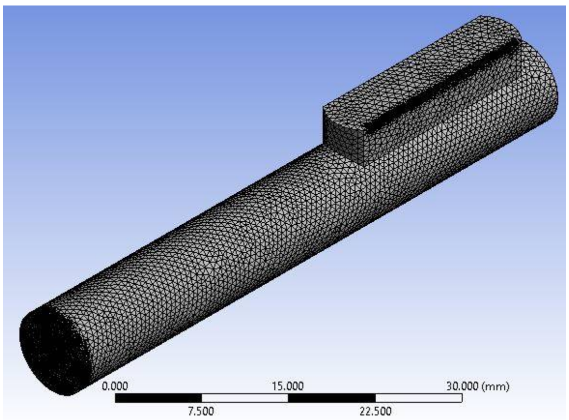
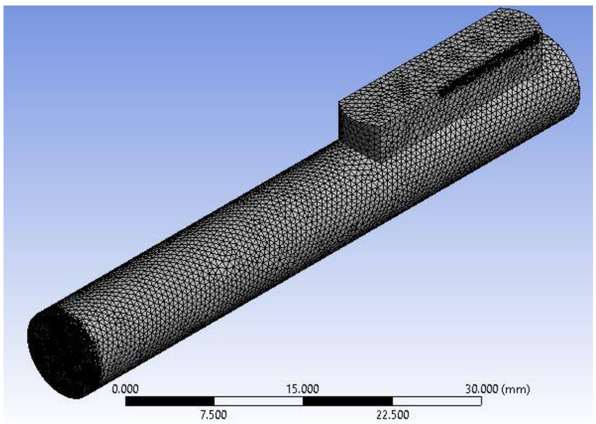
Table 2. Details of Meshing Information for all different index angle at 0.316 mm opening.

Details of Mesh		For 0^0 index angle 0.316 mm port opening	For 1^0 index angle 0.316 mm port opening	For 2^0 index angle 0.316 mm port opening	For 3^0 index angle 0.316 mm port opening
Defaults	Physics Preference	CFD	CFD	CFD 1	CFD 1
	Solver Preference	Fluent	Fluent	Fluent	Fluent
	Relevance	100	100	100	100
Sizing	Used Advanced size function	curvature	curvature	curvature	curvature
	Relevance Centre	Fine	Fine	Fine	Fine
	Smoothing	High	High	High	High
	Transition	Slow	Slow	Slow	Slow
	Span angle centre	Fine	Fine	Fine	Fine
	Curvature normal angle	12^0	12^0	12^0	12^0
	Min. Size	0.005938 mm.	0.005938 mm.	0.005938 mm.	0.005938 mm.
	Max. Face Size	0.5938 mm.	0.5938 mm.	0.5938 mm.	0.5938 mm.
	Max .size	1.1876 mm.	1.1876 mm.	1.1876 mm.	1.1876 mm.
	Minimum Edge length	0.02 mm.	0.02 mm.	0.02 mm.	0.02 mm.
Statistics	Nodes	29774	29686	28524	28128
	Elements	151585	151052	145851	143993



(a) Meshed model of 0^0 index angle 0.316 mm port



(b) Meshed model of 1^0 index angle 0.316 mm port

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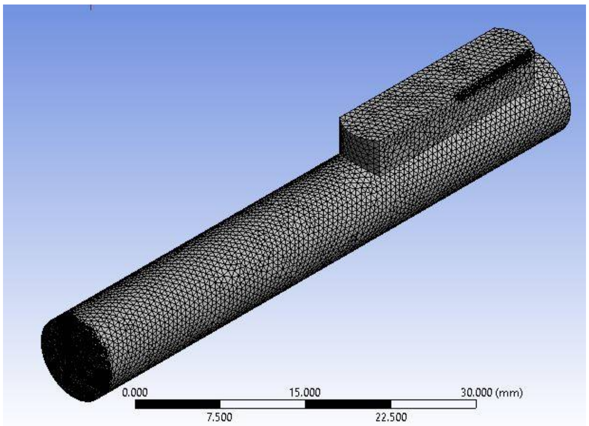
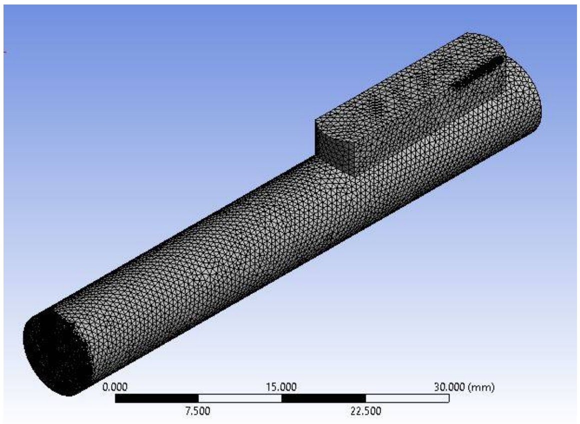


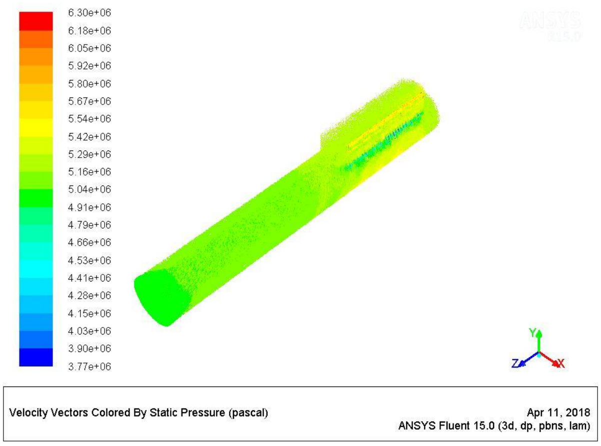
(c) Meshed model of 2⁰ index angle 0.316 mm port



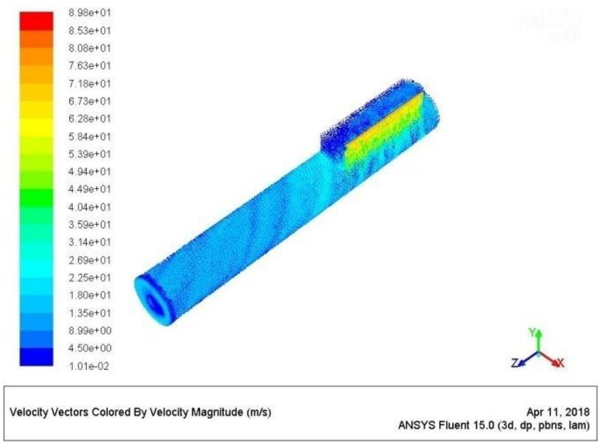
(d) Meshed model of 3⁰ index angle 0.316 mm port

Figure 16. Meshed model for all different index angle at 0.316 mm

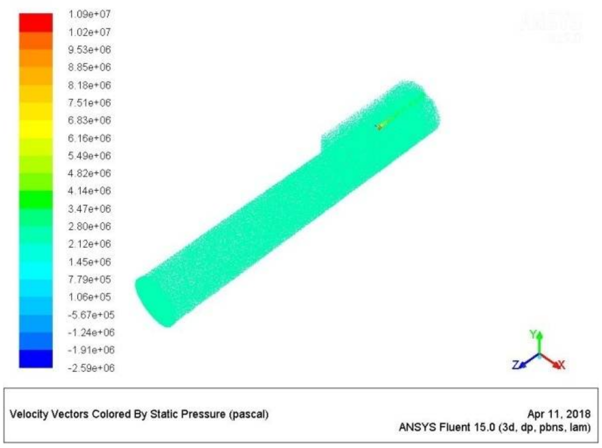
Figure 17 [(a) to (h)] show the velocity and pressure streamlines for various spool geometries at 0.316 mm port opening, and it can be shown that for the spool groves index angle change from 0 degree to 3 degrees, the flow patterns are highly varied. The fluid velocities are suddenly increased at the groove entrance region and nearly same upto the middle region for different geometric design of the spool valve groove. Also the flow directions are rapidly changed at the entrance of the groove. Therefore, pressures at the groove entrance are varied with change in groove geometry. In Fluent the boundary conditions are same for all four (each have different groove geometry) analysis and the flow rate is kept constant.



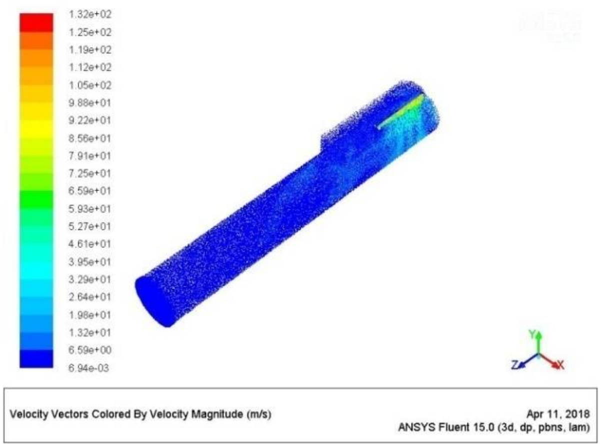
(a) Static pressure for 0⁰ index angle 0.316 mm port



(b) Velocity vector for 0⁰ index angle 0.316 mm port



(c) Static pressure for 1⁰ index angle 0.316 mm port



(d) Velocity vector for 1⁰ index angle 0.316 mm port

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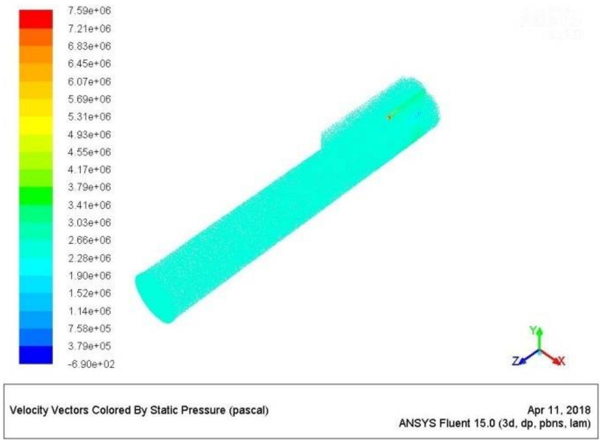
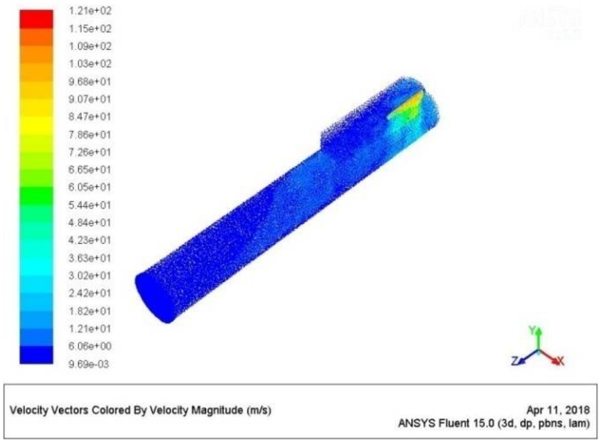
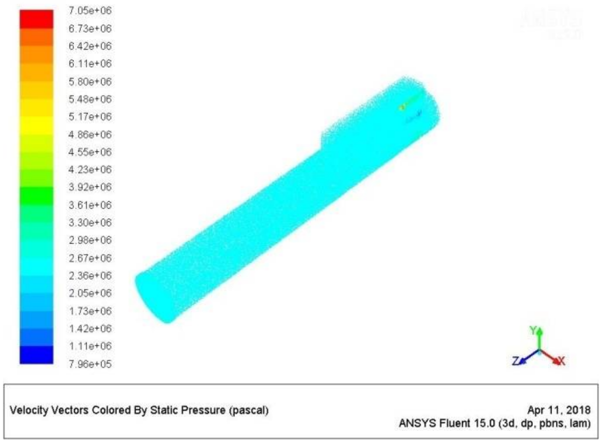


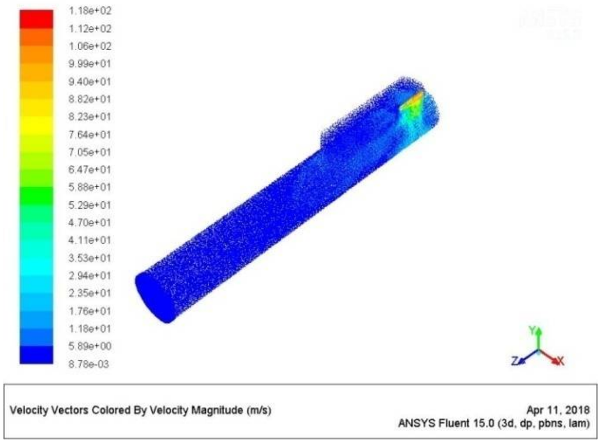
(e) Static pressure for 2^0 index angle 0.316 mm port



(f) Velocity vector for 2^0 index angle 0.316 mm port



(g) Static pressure for 3^0 index angle 0.316 mm port



(h) Velocity vector for 3^0 index angle 0.316 mm port

Figure 17. Static pressure and velocity vector for all different index angle at 0.316 mm

7. Results and Discussions

After analyzing the pressure and the velocity vector for different index angle of the spool valve the common observation are as under:

- For the opening of 0.316 mm of spool groove linear displacement i.e. which is equal to 0.857 degree of spool valve shaft rotation from initial neutral position, the pressure on other side of orifice opening is very high because the major pressure drop takes place at less than 0.25 mm of opening.
- As the opening is increased gradually, the pressure increase is continuous and follow the analytical results. Thus the FLUENT results are comparable with the analytical results.
- Velocity vector also follow the continuous pattern, for less opening of spool groove the velocities are very high at the orifice and gradually reduce, on increase in the opening.
- The pressure and velocity profile is continuous and regular and no irregularities are observed through the fluid flow path.

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Table 3. Pressure drops at the spool port openings.

Geometry	Opening (mm)	Shaft rotation (deg)	Pressure at orifice (MPa)
0 deg index angle	0.1	0.2712	3.43 – 3.64
	0.2	0.5425	4.65 – 4.81
	0.316	0.857	5.42 – 5.54
	0.4	1.0849	7.32 – 7.66
1 deg index angle	0.1	0.2712	3.26 – 3.33
	0.2	0.5425	4.14 – 4.46
	0.316	0.857	6.74 - 7.65
2 deg index angle	0.158	0.428	2.89 – 3.56
	0.316	0.857	3.41 - 4.15
	0.474	1.286	5.85 – 6.45
	0.632	1.714	7.85 – 7.93
3 deg index angle	0.158	0.428	3.61 – 3.92
	0.316	0.857	3.79 – 4.11
	0.474	1.286	5.12 - 5.45
	0.632	1.714	5.71 – 6.15
	0.790	2.1428	6.65 - 7.45
	0.948	2.552	7.65 – 7.95

8. Conclusions

The pressure drop at the entrance of the flow passage and the pattern of pressure build up inside the chamber with respect to spool valve (main shaft) rotation is carried out using analytical technique (MATLAB). By comparative study with the numerical technique, which is also used to analyze the flow pattern characteristics, pressure and velocity distribution inside the flow passage shows a good agreement. Using Fluent (CFD) it is observed that there are no irregularities in pressure and velocity streamlines exists along the fluid flow path for different spool valve geometries. Various geometric designs for the spool groove were analyzed and it is observed that for more simple design with low index angle of the groove, the pressure drops are abrupt in nature and pressure hikes/ rises inside the chamber is very quick. Such type of pressure rise/hike gives erratic behavior during very slow speed and high precision operations of the hydrostatic unit. By increasing the index angle from 0 degree to 3 degrees a continuous improvement in reducing the pressure irregularities is observed.

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