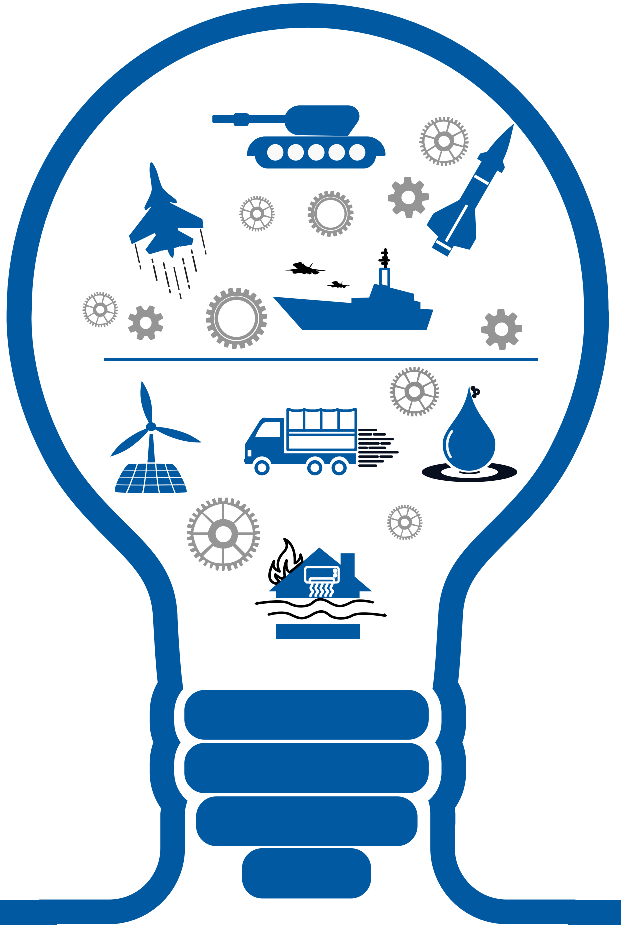
Preliminary Sizing & Design of Axial Piston Pump

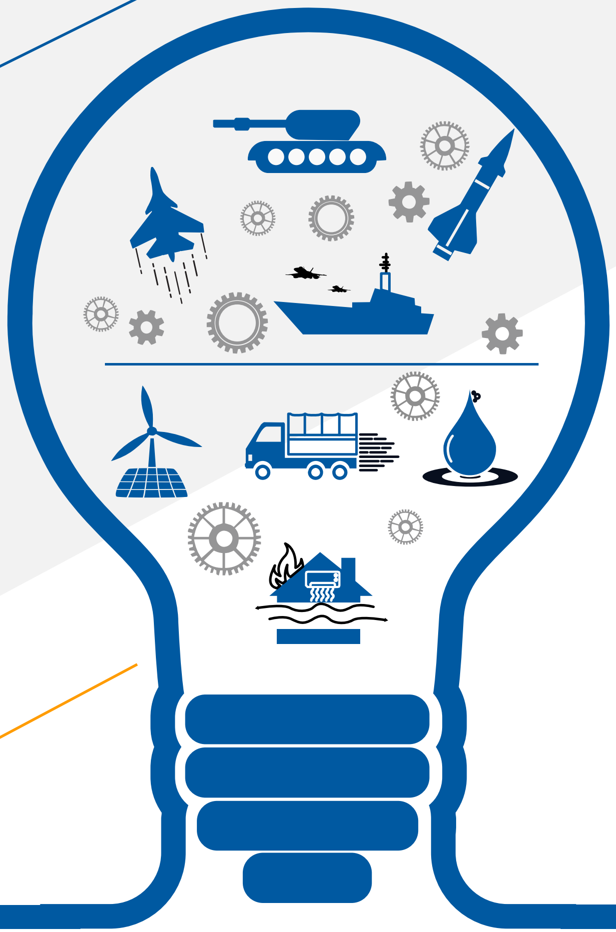
Manual for Theory & Usage

Abhishek Jain

Zeus Numerix Pvt. Ltd.

abhishek@zeusnumerix.com





Governing Equations & Mathematical Modeling

References, Governing Equations & Input / Output

References Used

- In order to arrive at preliminary sizing, it is important for being able to simulate the operation of the axial piston design. The simulation should predict the time history of cylinder pressures & associated leakages to predict the efficiency of axial pump design. A mathematical model is thus developed.
- Reference is made to a 2016 PhD thesis “Interaction of Bootstrap Reservoir and Hydraulic Pump in Aircraft Hydraulic Systems” by J. Aaltonen (Tampere Univ. of Tech.)
- The mathematical model in this thesis is derived from “Hydrostatiche Pumpen und Motoren: Konstruktion und Berechnung” (1993) by J. Ivantysyn & M. Ivantysynova.
- Mathematical model is developed for Constant Flow Axial Piston Pump with Fixed Swash Plate

Governing Equations: Piston Pressure

- Pressure inside single pumping piston (p_k) is result of three time dependent factors: (i) speed of piston, (ii) flow through port plate orifices & (iii) leakage flows.

$$p_k = p_{k0} + \int_0^t \frac{dp_k}{dt} dt$$

$$\frac{dp_k}{dt} = \frac{B}{V_c}\left[\frac{dV_c}{dt} - Q_{kp} - Q_{ks} - Q_{kL}\right]$$

Compressibility of fluid relates net flow rate into piston with rate of pressure rise

$$V_c = V_{c0} - A_k x_{Dk}$$

Volume of each cylinder is function of piston linear displacement

$$x_{Dk} = R[tan\beta(1 - cos\varphi)]$$

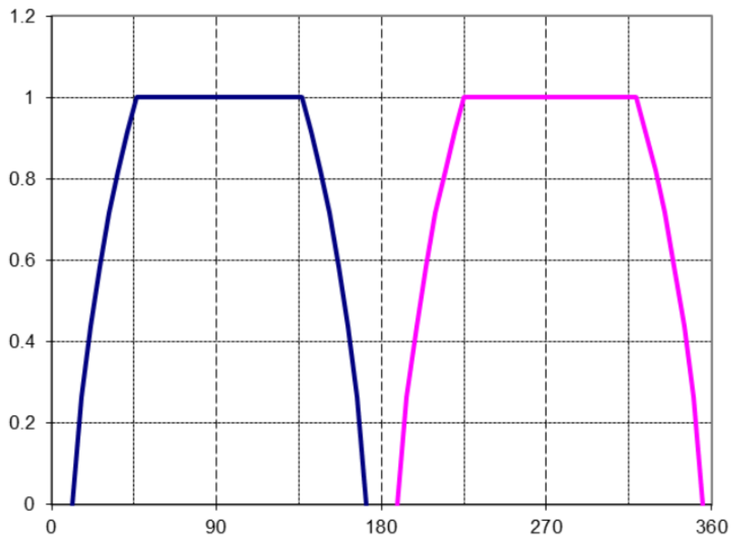
Instantaneous piston position depends on the swash plate angle & circumferential position of piston in rotating barrel

Governing Equations: Port Flow

- Flow through Suction & Discharge Port

$$Q_{kp} = c_d A'_p \sqrt{\frac{2(p-p_k)}{\rho}}\, sgn(p-p_k)$$

$$Q_{ks} = c_d A'_s \sqrt{\frac{2(p_s-p_k)}{\rho}}\, sgn(p_s-p_k)$$



Flow rate dependent on pressure difference across valve plate ports

For detailed design, CFD simulations should be done to maximize discharge coeff.

Area opening ratio of suction & discharge ports is a function of circumferential angle

The tapering of port area is a matter of detailed design study

Governing Equations: Flow Leakages

- There are total of three sources of flow leakages that have been modeled:

$$Q_{cL} = \pi v_k \frac{D_k}{2} h_{0k} + \frac{\pi D_k h_{0k}^3}{24\eta} \frac{(p_k - p_e)}{l_k} \left[1 + 1.5 \left(\frac{e}{h_{0k}} \right)^2 \right]$$

Leakage around piston cylinder volume and casing; Dependent on radial clearances & oil viscosity

$$Q_{iL} = \frac{wh^3}{12\mu} \frac{dp}{dx} = \frac{w_i \left(h_0 - r_i \tan\psi \cos\varphi_i \right)^3}{12\mu} \frac{dp}{dx}$$

Flow leakage from piston cylinder through gap between barrel & valve plate

$$Q_{sL} = \frac{\pi h_G^3}{6\eta ln\left(\frac{R_G}{r_G} \right)} p_k$$

Flow leakage from piston cylinder through slipper pad at contact with swash plate

- All the above add to the flow rate that is drained out of pump casing.
- Pressure in pump casing also depend on design & size of drain port, which in turn affect the case drain flow .

Governing Equations: Drive Torque

- Drive torque on the pump shaft depends on the forces acting on the rotating group (barrel / piston assembly):

$$M_{Bz} = \sum_{i=1}^{z} x_{Ri} F_{RByi} - \sum_{i=1}^{z} y_{Ri} F_{RBxi}$$

Forces are acting on the rotating barrel through pistons & its pressurized cylinders

$$F_{RByi} = F_{Skyi} + F'_{\omega kyi} + F_{TGyi} \quad ; \quad F_{RBxi} = F'_{\omega kxi} + F_{TGxi}$$

Net forces are sum of force from piston, centrifugal force & friction at slipper

$$F_{Sky} = F_{Aki} \tan\beta$$

$$F_{Aki} = F_{Dki} + F_{aki} + F_{Tki}$$

$$F_{Dki} = A_k (p_k - p_e)$$

From fluid pressure

$$F_{aki} = m_k a_{ki}$$

From piston acceleration

$$F_{Tki} = f_k F_{Rki} \operatorname{sgn}(-v_k) + b_k v_k$$

From piston frictional force

Input / Output to Math Model

- Code is implemented in ‘C’; I/O for constant volume operations are:

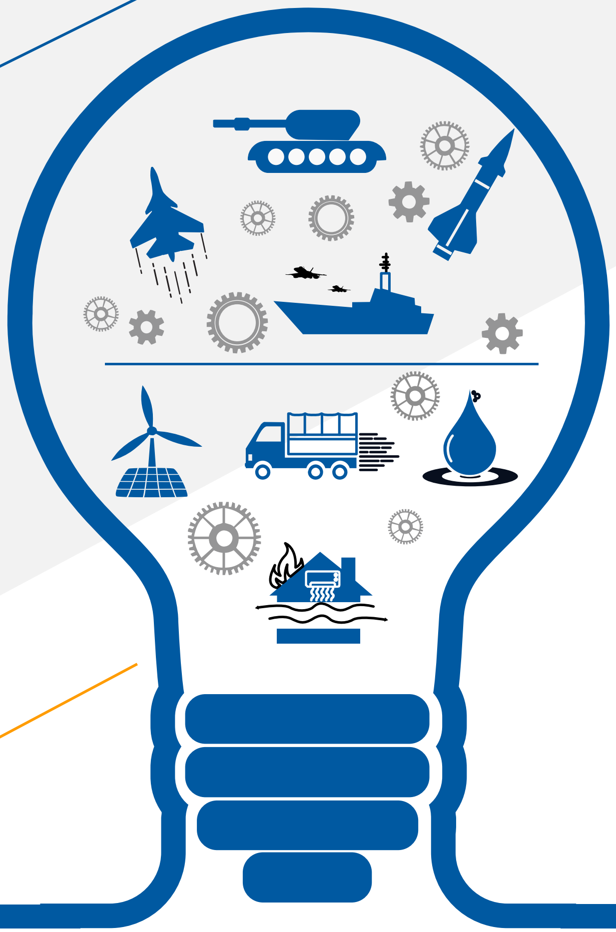
Pump Design Parameters	
No. of Pistons	7
Diameter of Piston	9.5 mm
Length of Piston	50.0 mm
Mass of Piston	30 gm
Nominal Dead Vol.	3.0 cc
Radius Piston Bore	27.5 mm
Swashplate Angle	16.0 Deg
Area Pressure Port	55 sq.mm
Area Suction Port	55 sq.mm
Discharge Coeff. Port	1.0
Orifice Drain Port	10 sq.mm
Discharge Coeff. Drain Port	0.2

Clearances & Friction Factors	
Clearance Piston - Barrel	35 microns
Eccentricity Piston	10 microns
Clearance Valve Plate - Barrel	35 microns
Lubrication Film Thickness Slipper	10 microns
Fric. Coeff. Piston Barrel	0.3 Ns/m
Fric. Coeff. Swashplate Slipper	0.3 Ns/m

Operating Conditions	
Suction Pressure	4.5 Bar
Discharge Pressure	260 Bar
Shaft Speed	4450 RPM

Fluid Properties	
Density	882 Kg/m3
Bulk Modulus	-1.93 Gpa
Dynamic Viscosity @ 90^{o}C	0.00617 Pa.s

PUMP PERFORMANCE (OUTPUT)	
Suction & Discharge Flow	33.2 & 30.2 LPM
Case Drain Flow & Pressure	2.5 LPM & 15.5 Bar
Drive Torque & Efficiency	32.0 Nm & 86.1 %

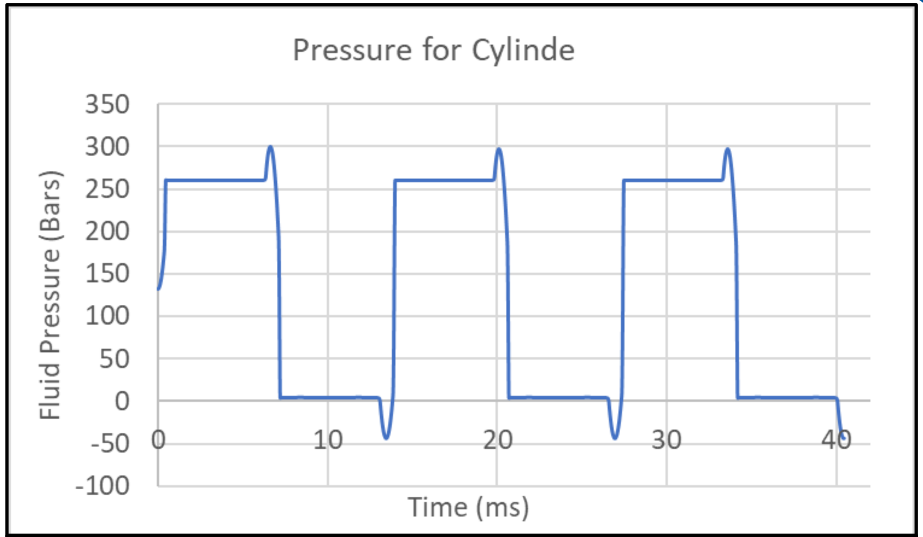


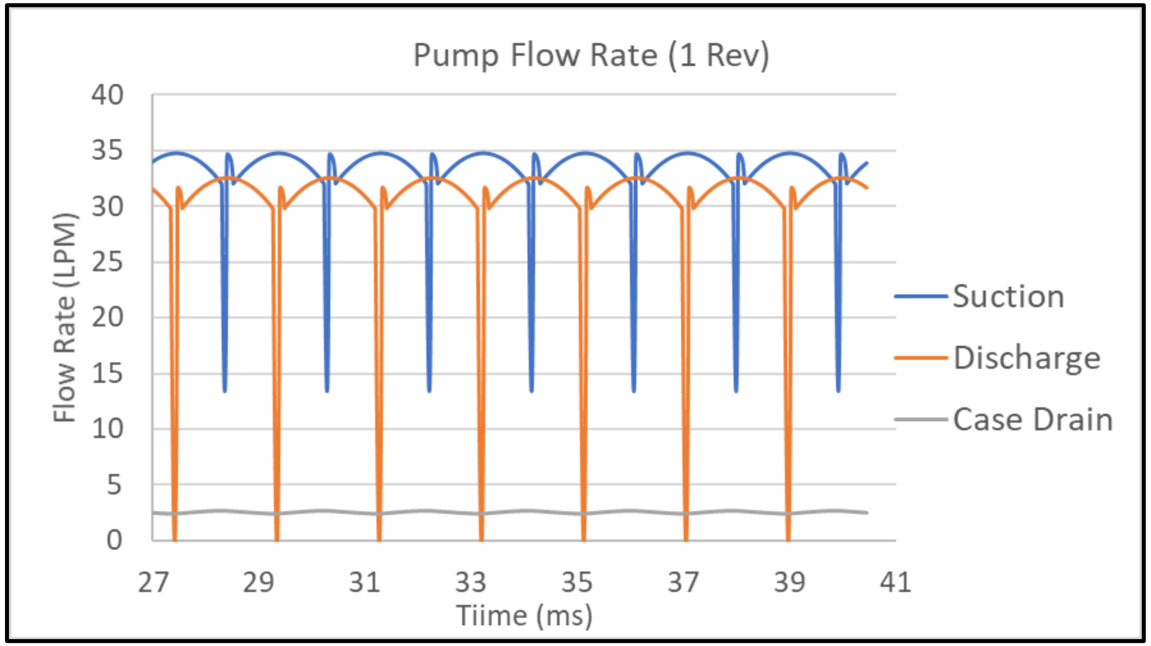
Sample Calculations & Sensitivity Analysis

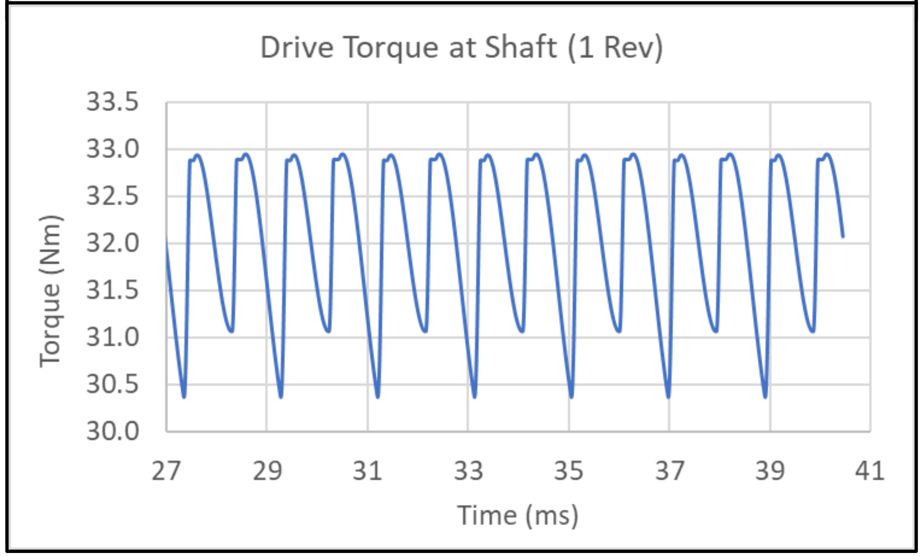
Impact of Operating Conditions & Design Parameters

Performance Parameter Variations

- We observe oscillations of flow & torque output from the pump
- Sudden jumps / drops are effect of cylinders passing over closed regions of the valveplate.

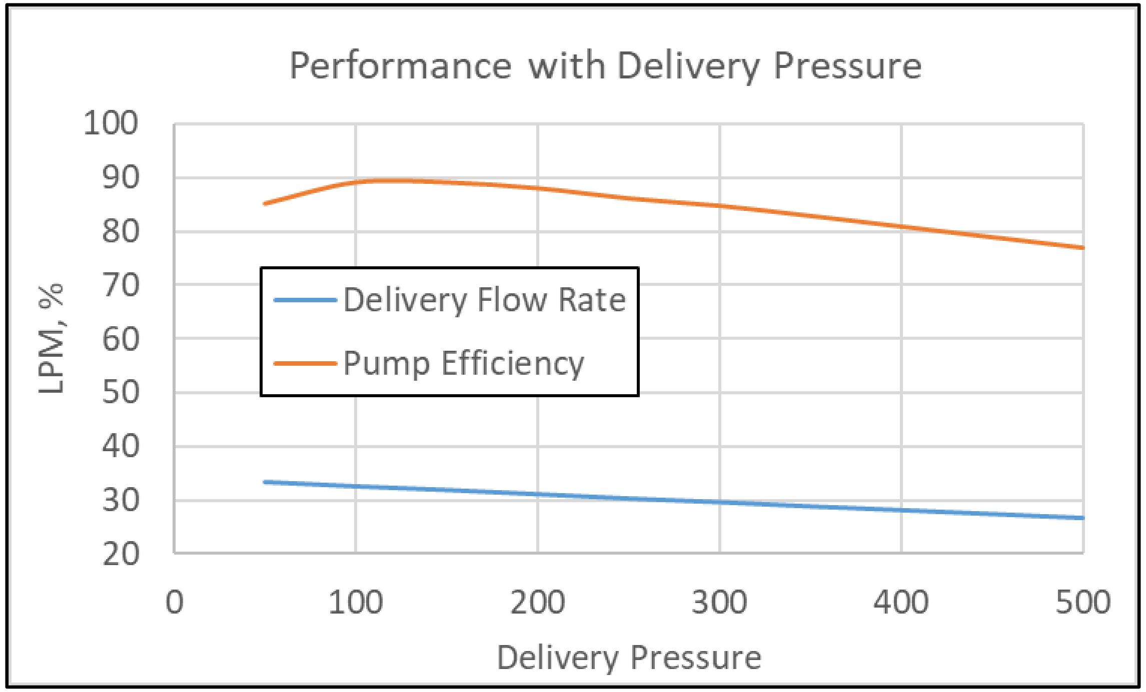


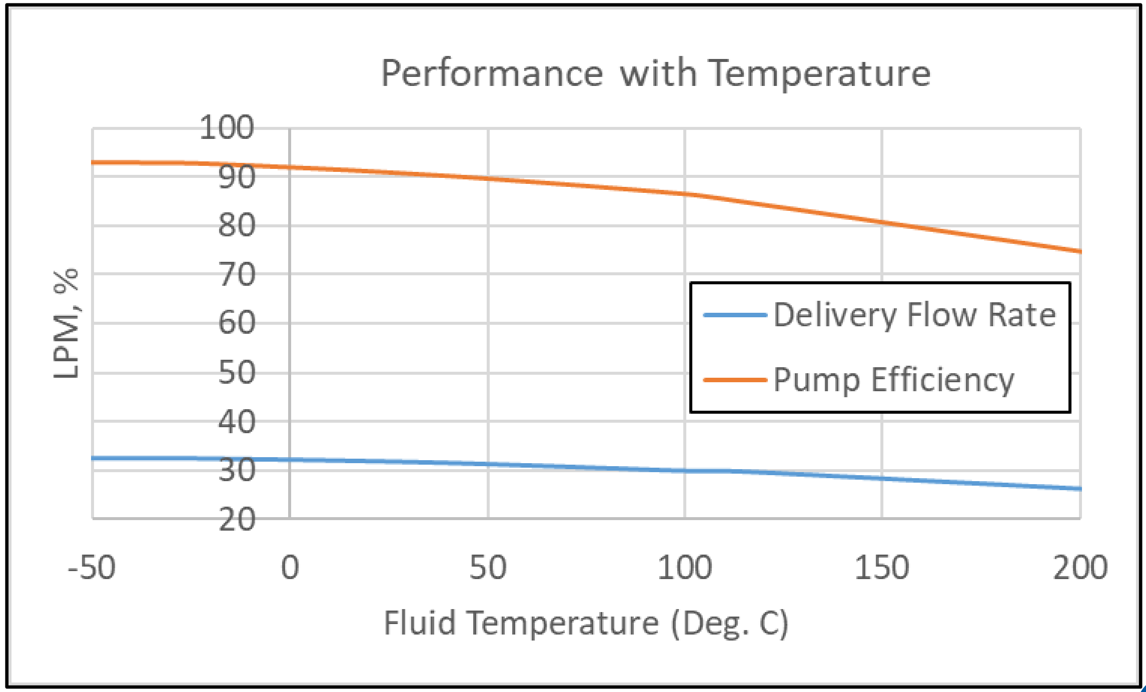




Operating Range of Engine Driven Pump

- As expected of fixed swashplate constant flow axial pump, there is no major flow rate change with changing discharge pressure. Pump is designed around its max efficiency
- As lower temperature, viscosity increases, leading to reduced leakage from cylinders into case. This results in slightly higher delivery flow rate & pump efficiency





Sensitivity to Design Variables

- Three set of design parameters are varied to understand their impact on pump performance. The results below help identify & focus on criticalities:

Performance Parameter	Base Design		No. of Cylinder, Keeping Displacement / Rev Same			Discharge Coefficient at Drain Suction & Discharge Port			Clearances, Lubrication Thickness & Eccentricity	
			5 Cylinders	9 Cylinders		0.5x C_D	2.0x C_D		0.5x Tolerance	2x Tolerance
Discharge Flow (LPM)	30.2		31.1	29.3		30.2	30.2		32.5	17.0
Drain Flow (LPM)	2.54		1.95	3.10		2.56	2.58		0.15	12.0
Case Pressure (Bars)	15.5		14.7	16.4		21.5	14.0		13.5	57.8
Drive Torque (Nm)	32.0		31.9	32.3		32.0	32.1		32.0	32.2
Efficiency (%)	86.1		89.2	83.0		86.2	85.9		92.9	48.1

- Reducing number of cylinders improve efficiency, but it also reduces in higher pulsating flow.
- As can be seen, manufacturing tolerances play a major role in achieving high efficiency product. Precision manufacturing & precise assembly is critical for product development.

ZEUS NUMERIX

Abhishek Jain
+91 72760 31511
abhishek@zeusnumerix.com
www.zeusnumerix.com