Project 16ST1: AC Hydraulic Pump/Motor

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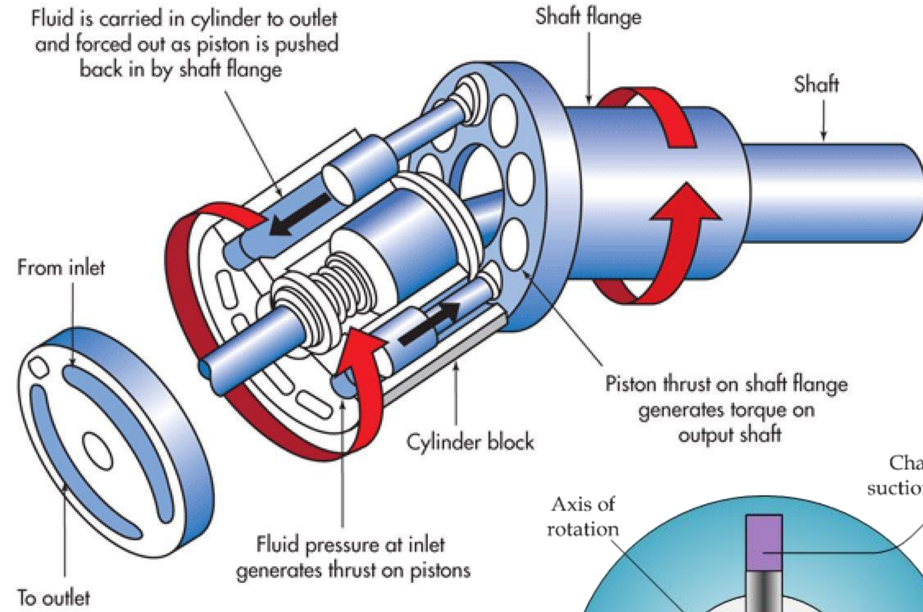
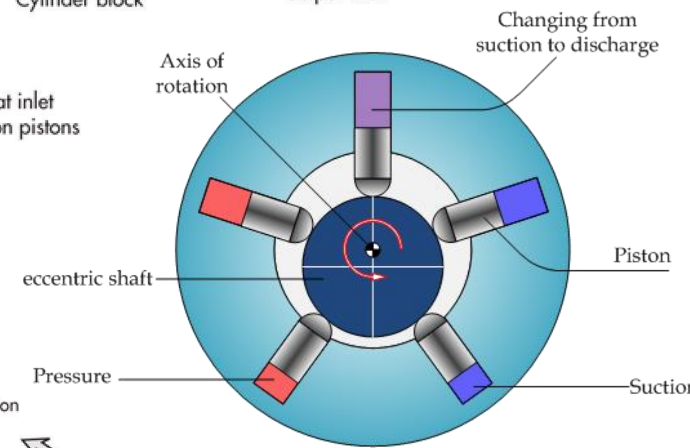
Hydraulic Pump

Common Fixed Displacement Pump:
- Gear Pump
- Vane Pump
- Bent Axis Pump
- Axial Piston Pump
- Radial Piston Pump

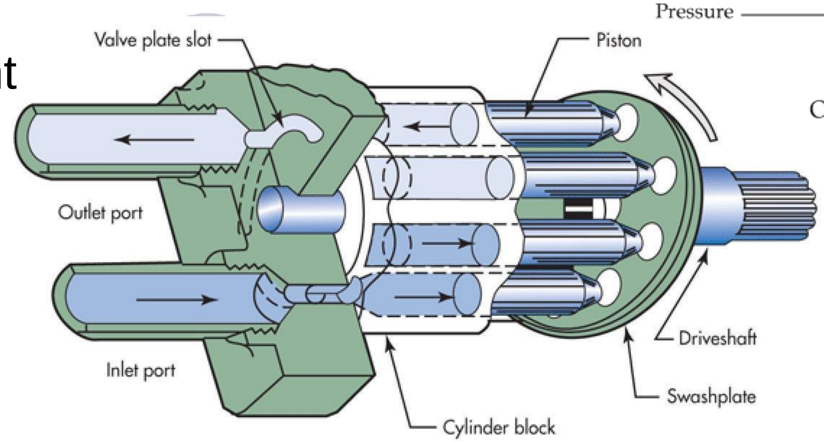
Common Variable Displacement Pump:
- Swash-Plate Axial Piston Pump
- Bent Axis Pump

Goal:
- Variable Displacement
- Compactness
- Simple Structure
- High Efficiency

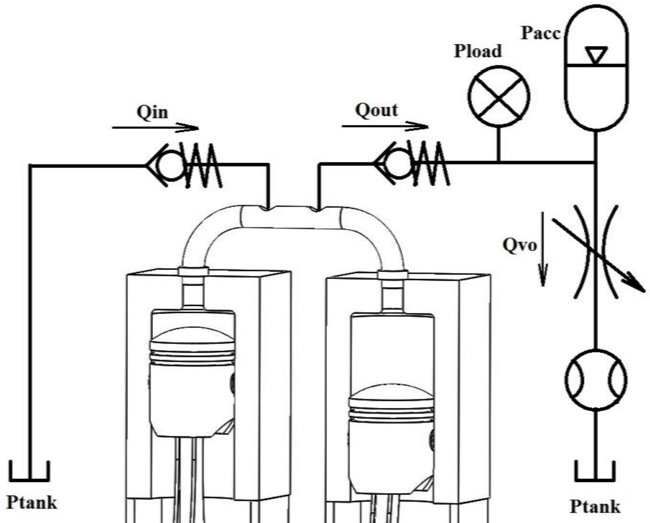


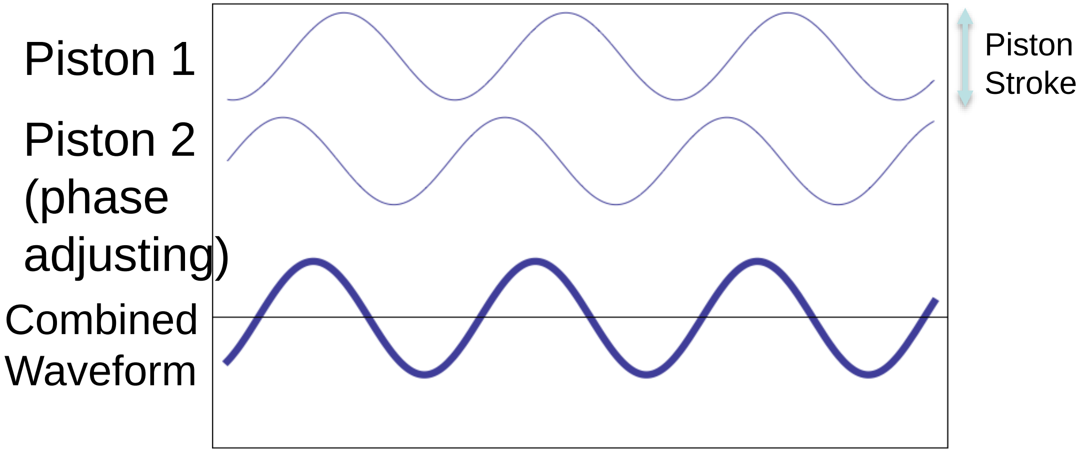


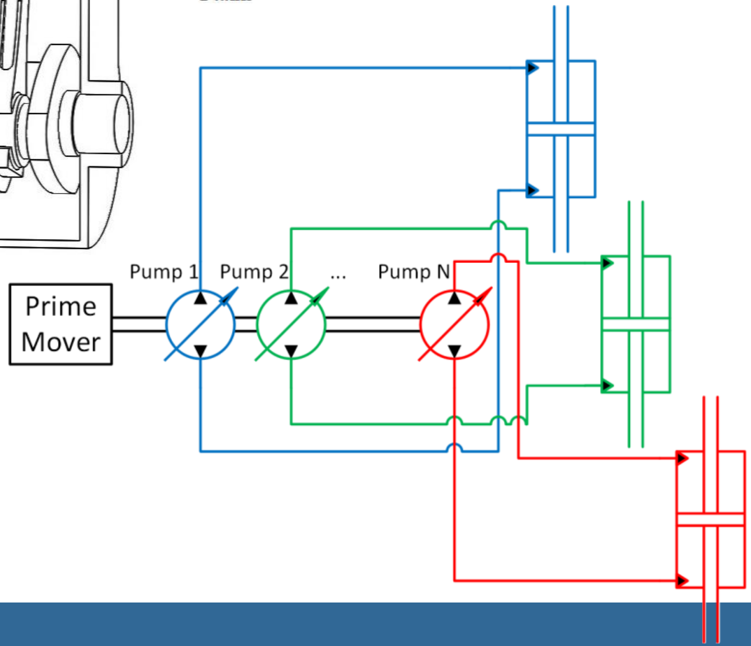
Outside impinged radial piston pump

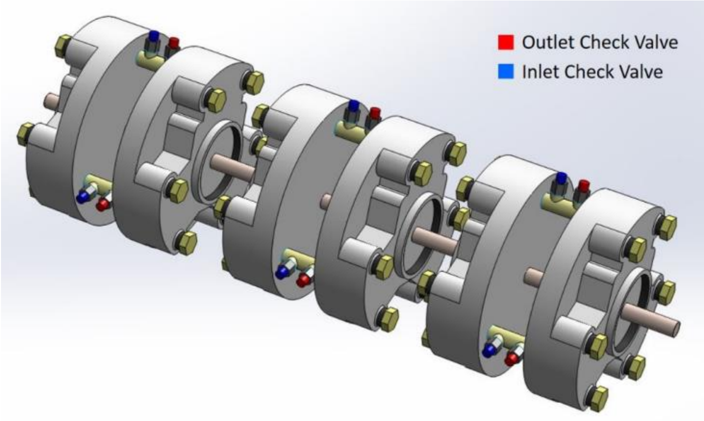


AFH Variable Displacement Pump



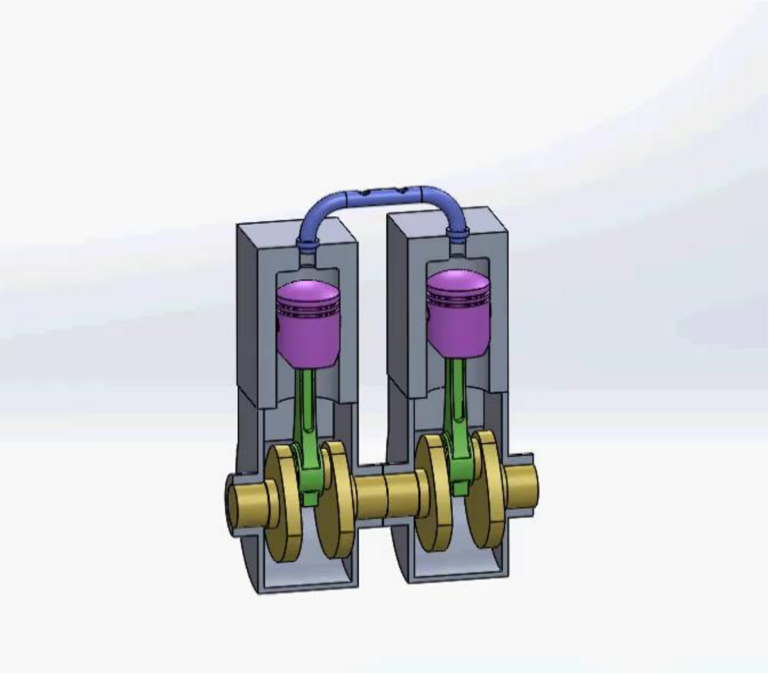


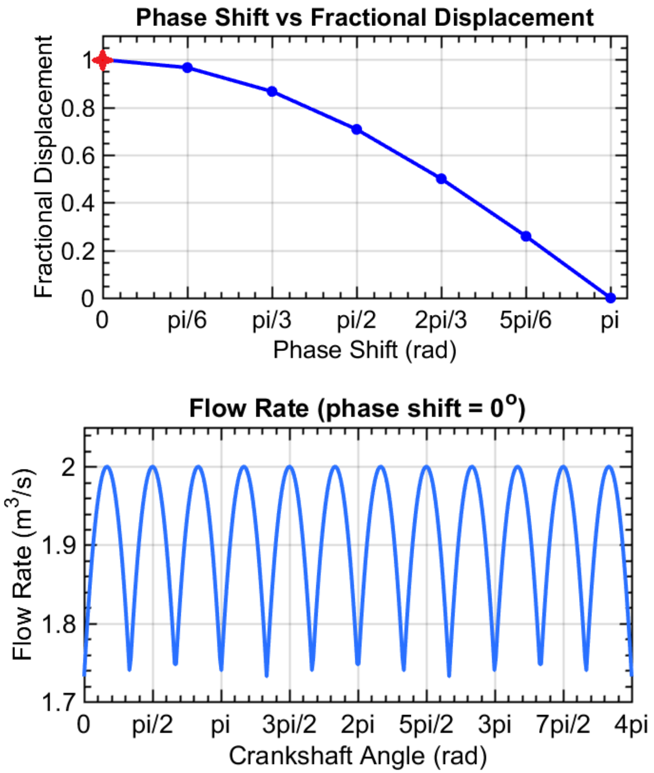




Basic Idea of AFH VDP

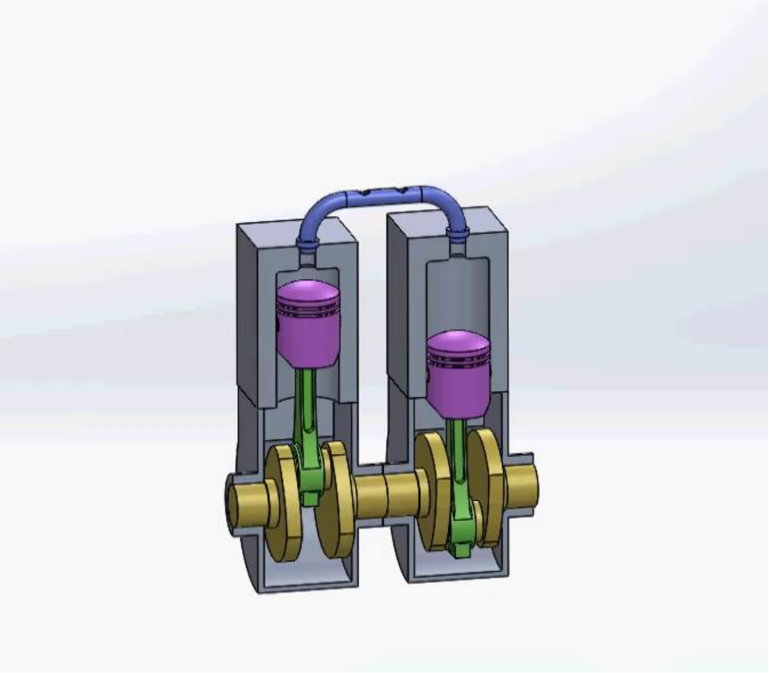
Phase Shift = 0°, Fractional Displacement = 1

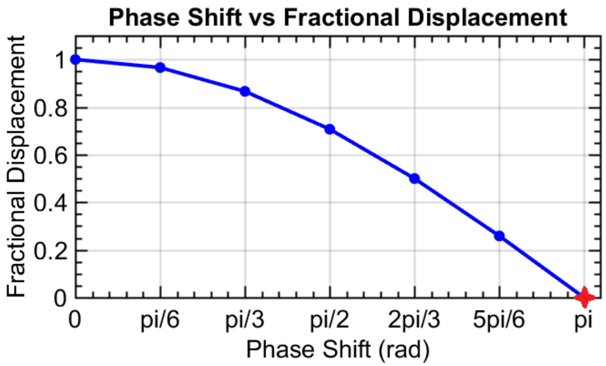


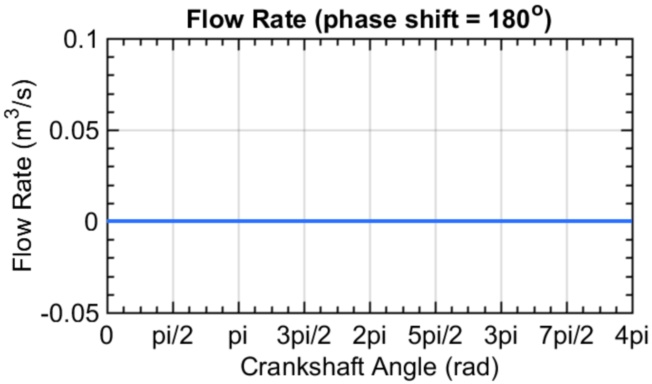


Basic Idea of AFH VDP

Phase Shift = 180°, Fractional Displacement = 0

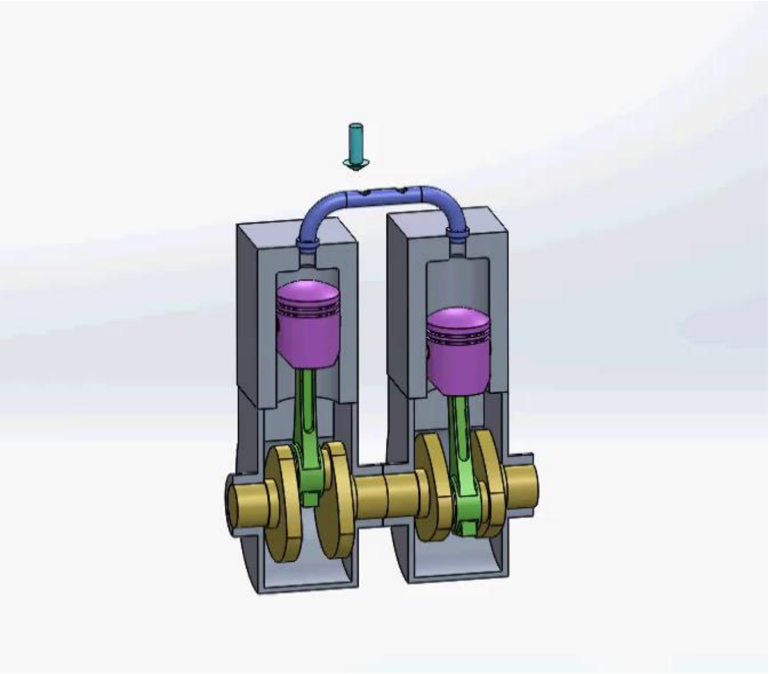


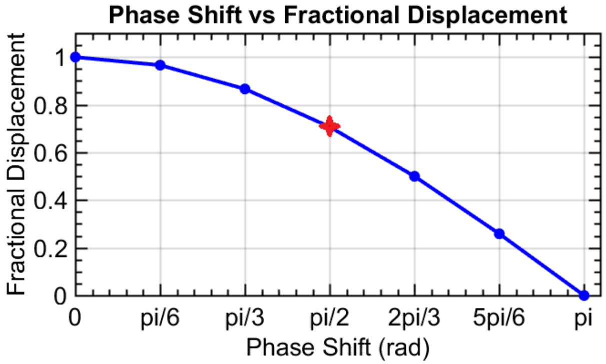


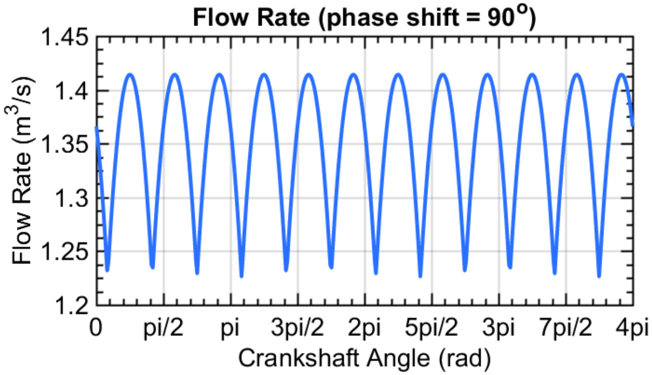


Basic Idea of AFH VDP

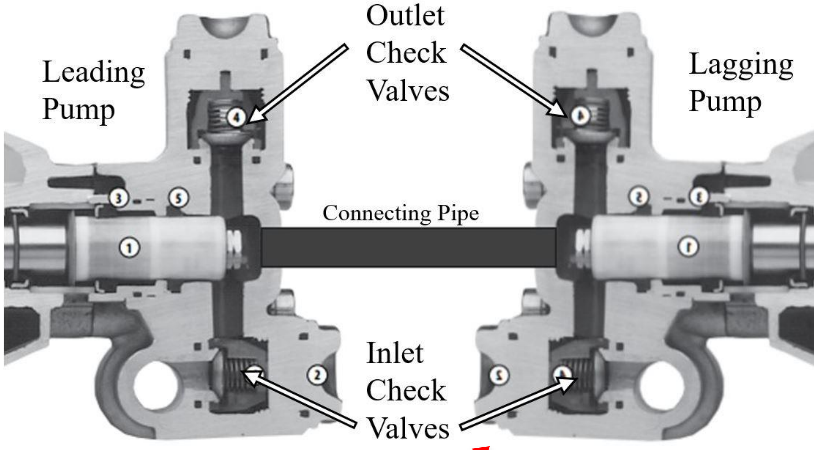
Phase Shift = 90°, Fractional Displacement = 70.83%

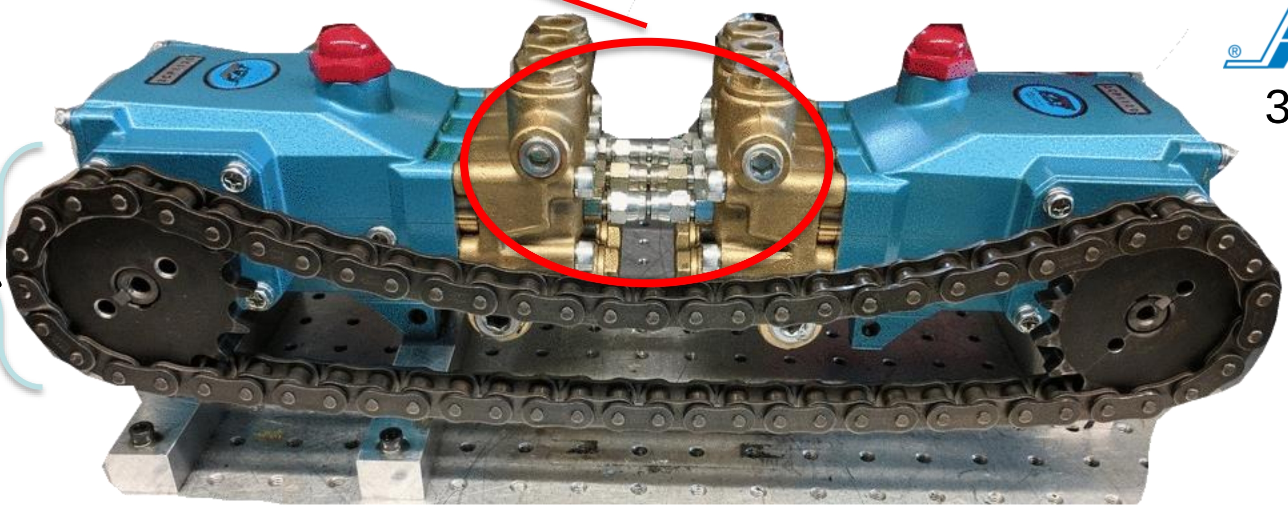






AFH VDP Prototype 1

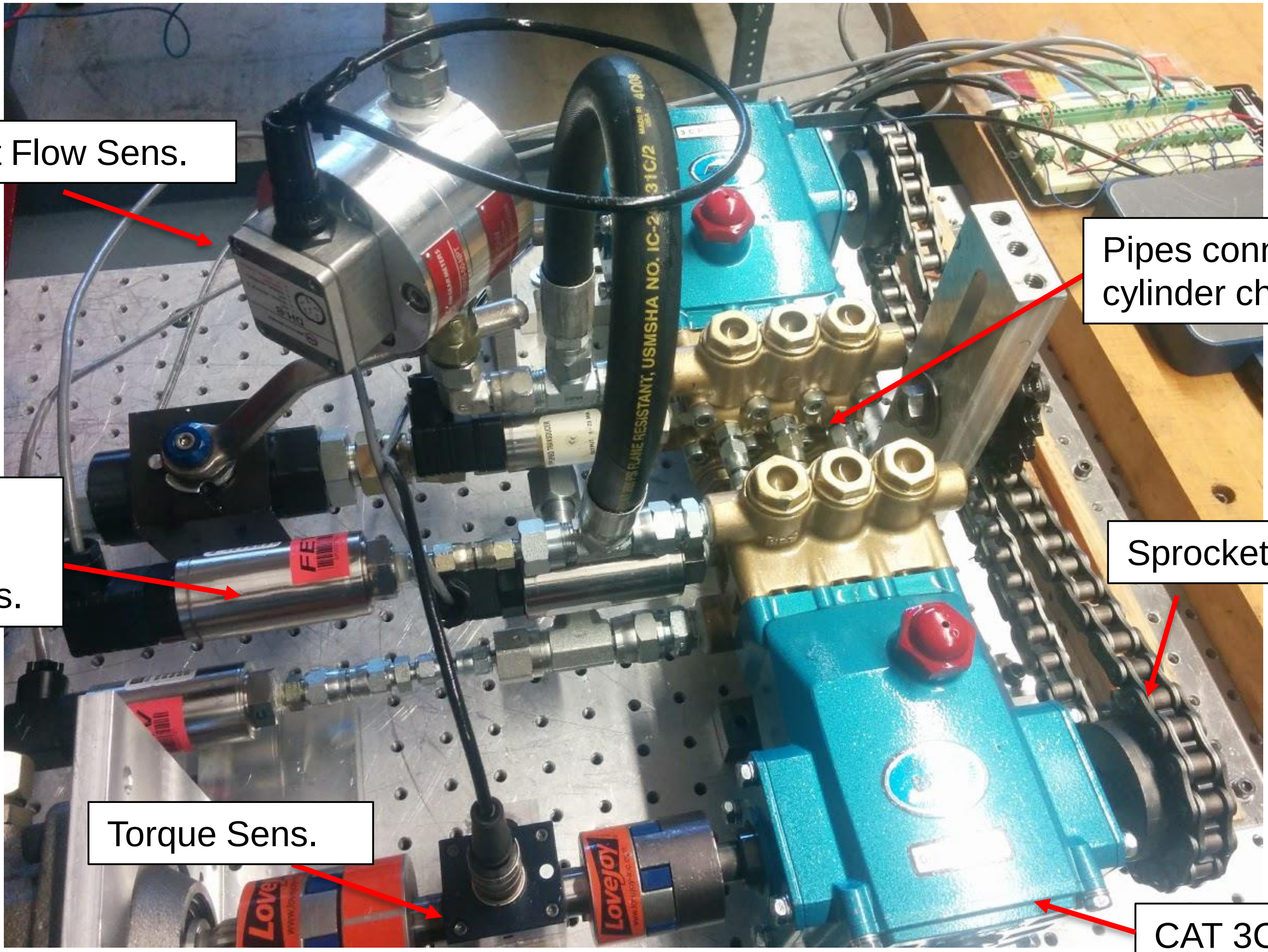




8 Discrete Phases

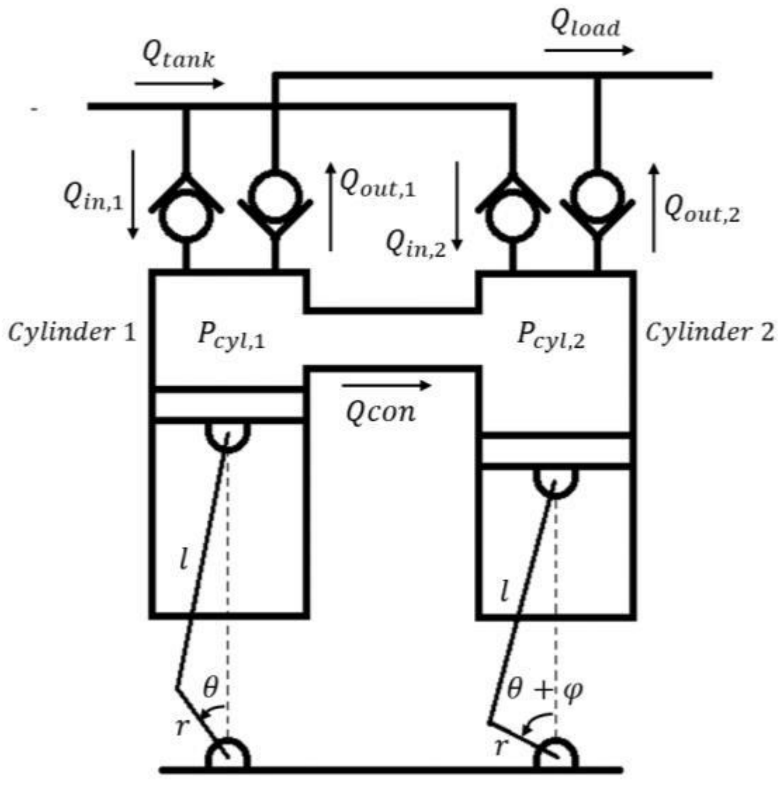
3CP1120

AFH VDP Prototype 1



AFH VDP Model

- The model captures piston kinematics and cylinder pressure as functions of the pump's phase shift angle.



$$y_1 = r(1 - \cos\theta) + l - \sqrt{l^2 - r^2 \sin^2\theta}$$

$$y_2 = r(1 - cos(\theta + \varphi)) + l - \sqrt{l^2 - r^2 \sin^2(\theta + \varphi)}$$

$$V_{cyl,1} = V_{tdc} + A_p\left[r(1 - cos\theta) + l - \sqrt{l^2 - r^2 \sin^2\theta}\right]$$

$$V_{cyl,2} = V_{tdc} + A_p\Big[r(1 - cos(\theta + \varphi)) + l$$
$$- \sqrt{l^2 - r^2 \sin^2(\theta + \varphi)}\Big]$$

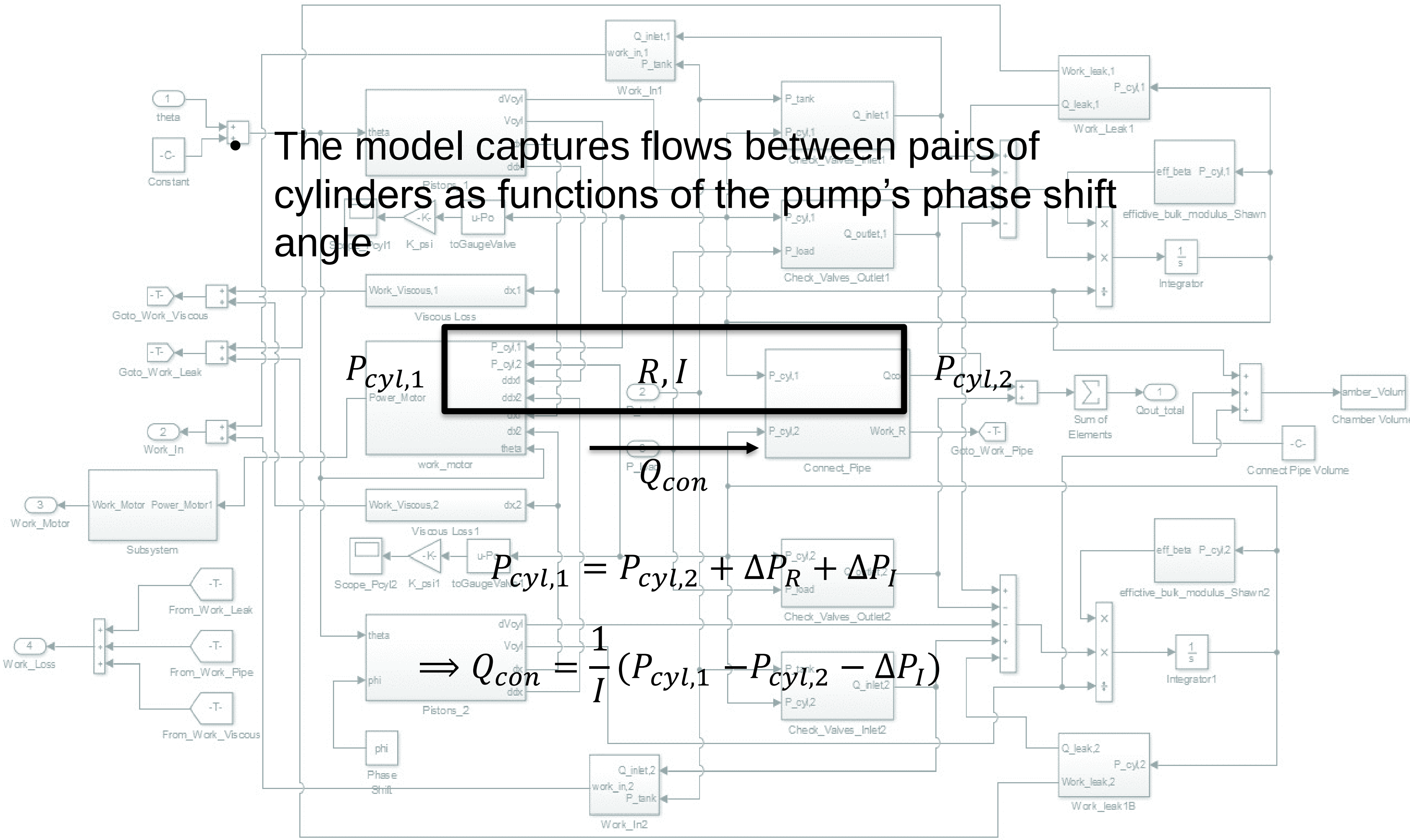
$$\dot{V}_{cyl,1} = A_p \omega r\left[1 + \frac{r\cos\theta}{\sqrt{l^2 - r^2\sin^2\theta}}\right]$$

$$\dot{V}_{cyl,2} = A_p \omega r\left[1 + \frac{r\cos(\theta + \varphi)}{\sqrt{l^2 - r^2\sin^2(\theta + \varphi)}}\right]$$

$$\dot{P}_{cyl,i} = \frac{\beta_{eff}}{V_{cyl,i}}\left(Q_{in,i} - Q_{out,i} - Q_{leak,i} - Q_{con} - \dot{V}_{cyl,i}\right)$$

AFH VDP Model

- The model captures flows between pairs of cylinders as functions of the pump's phase shift angle



$P_{cyl,1}$ R, I $P_{cyl,2}$

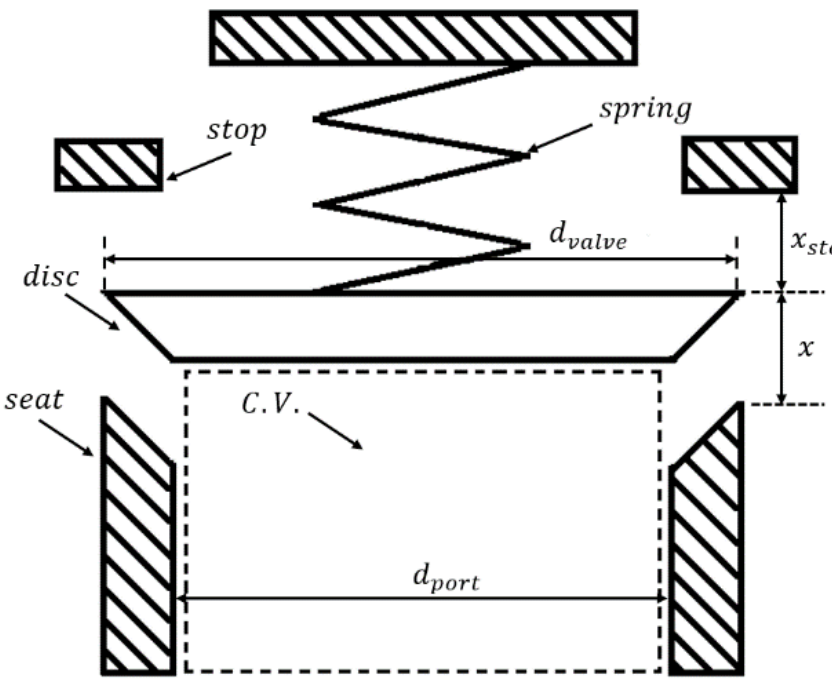
Q_{con}

$$P_{cyl,1} = P_{cyl,2} + \Delta P_R + \Delta P_I$$

$$\Rightarrow Q_{con} = \frac{1}{I}\left(P_{cyl,1} - P_{cyl,2} - \Delta P_I\right)$$

AFH VDP Model

- The model also captures check valve dynamics†



$$m_{disc}\ddot{x} = F$$

$$A_{valve}(x) = \max\left(0, \pi d_{port} x\right)$$

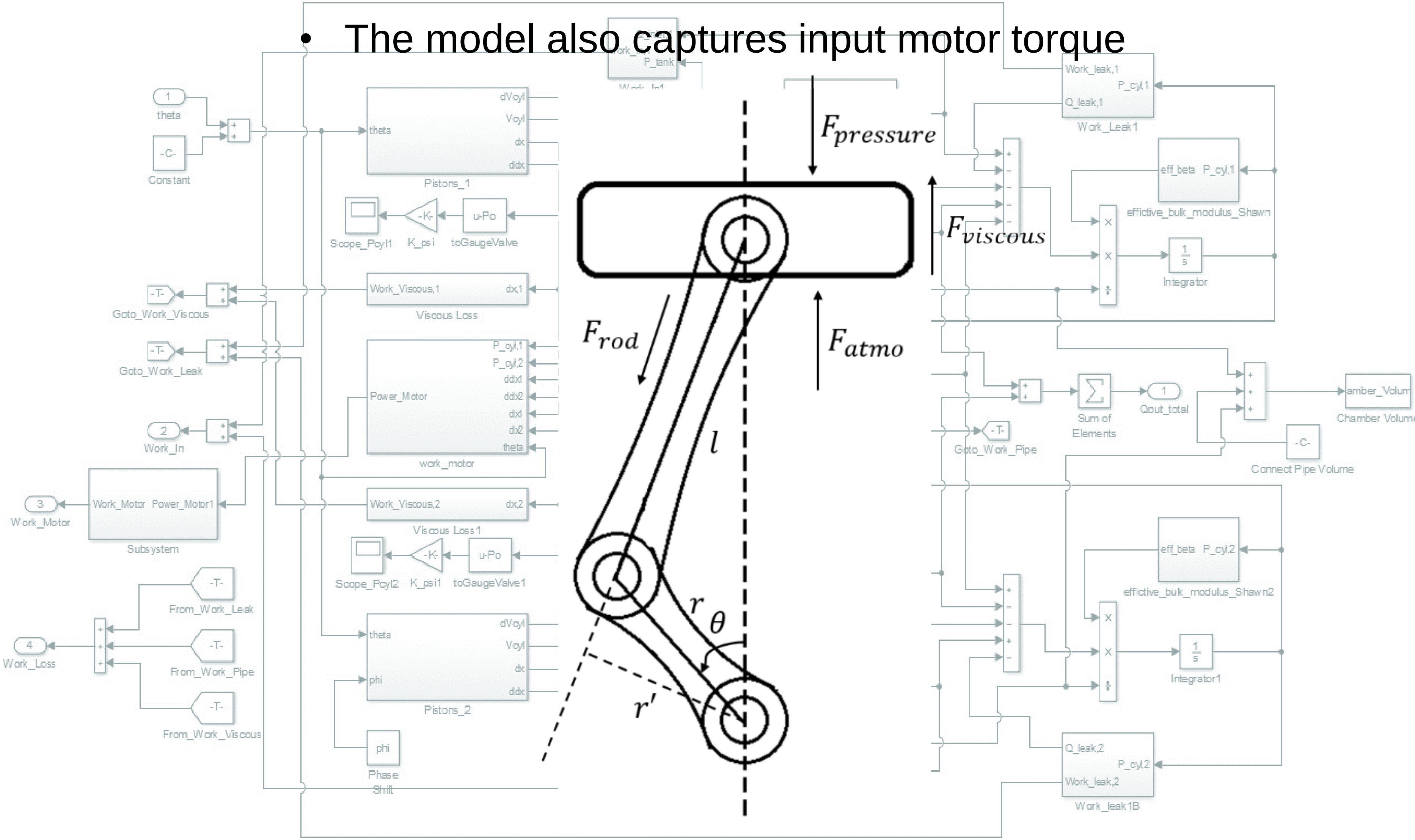
$$Q_{in,i} = C_{dvalvein} A_{valvein} \sqrt{\frac{2}{\rho}\Delta P_{in}}$$

$$Q_{out,i} = C_{dvalveout} A_{valveout} \sqrt{\frac{2}{\rho}\Delta P_{out}}$$

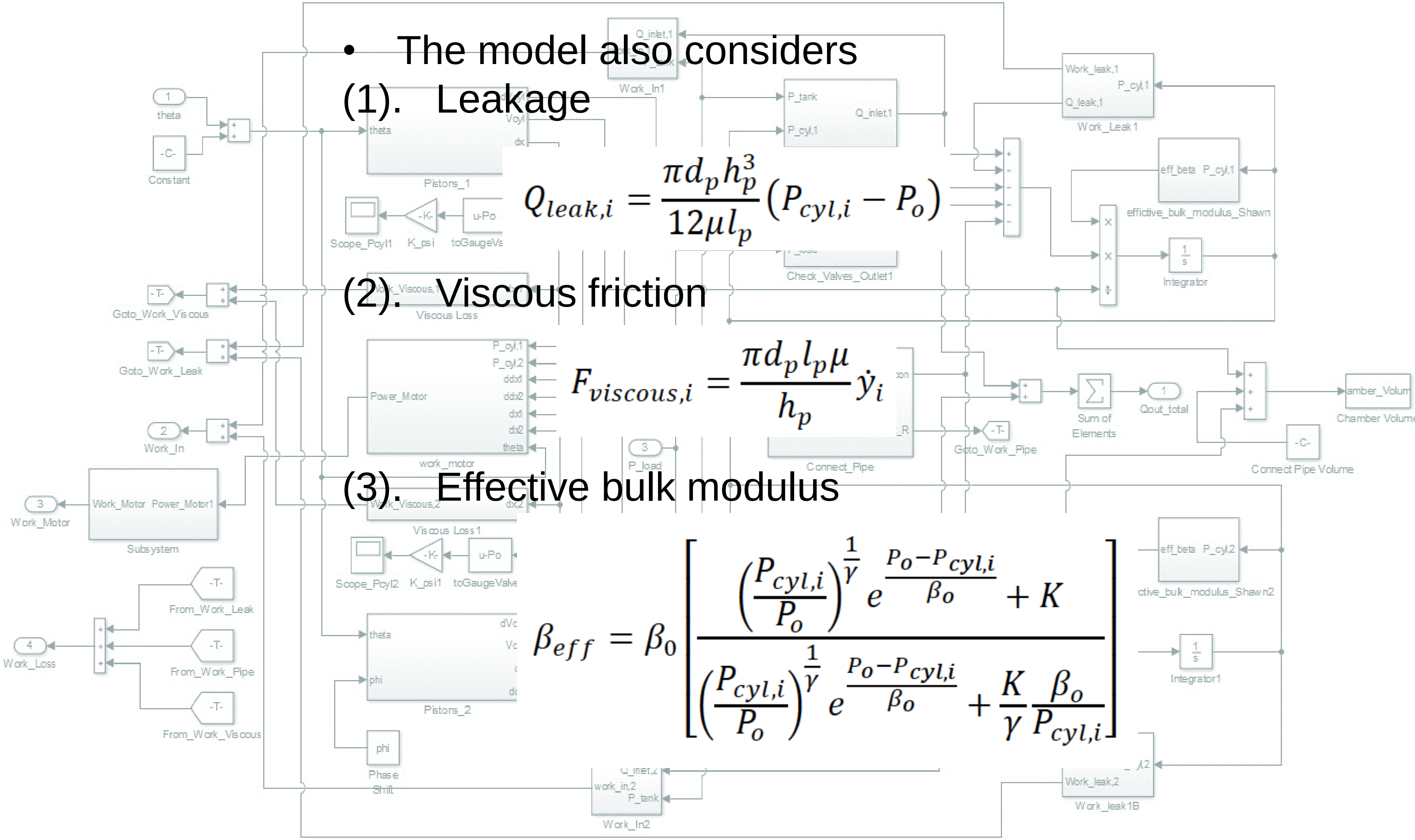
† Knutson, A. L., Van de Ven, J. D. (2016). Modelling and experimental validation of the displacement of a check valve in a hydraulic piston pump. International Journal of Fluid Power, 17(2), 114-124.

AFH VDP Model

- The model also captures input motor torque



AFH VDP Model



- The model also considers

(1). Leakage

$$Q_{leak,i} = \frac{\pi d_p h_p^3}{12 \mu l_p} \left(P_{cyl,i} - P_o \right)$$

(2). Viscous friction

$$F_{viscous,i} = \frac{\pi d_p l_p \mu}{h_p} \dot{y}_i$$

(3). Effective bulk modulus

$$\beta_{eff} = \beta_0 \left[\frac{\left(\frac{P_{cyl,i}}{P_o}\right)^{\frac{1}{\gamma}} e^{\frac{P_o - P_{cyl,i}}{\beta_o}} + K}{\left(\frac{P_{cyl,i}}{P_o}\right)^{\frac{1}{\gamma}} e^{\frac{P_o - P_{cyl,i}}{\beta_o}} + \frac{K}{\gamma} \frac{\beta_o}{P_{cyl,i}}} \right]$$

AFH VDP Model

A Dynamic Model using first principles captures

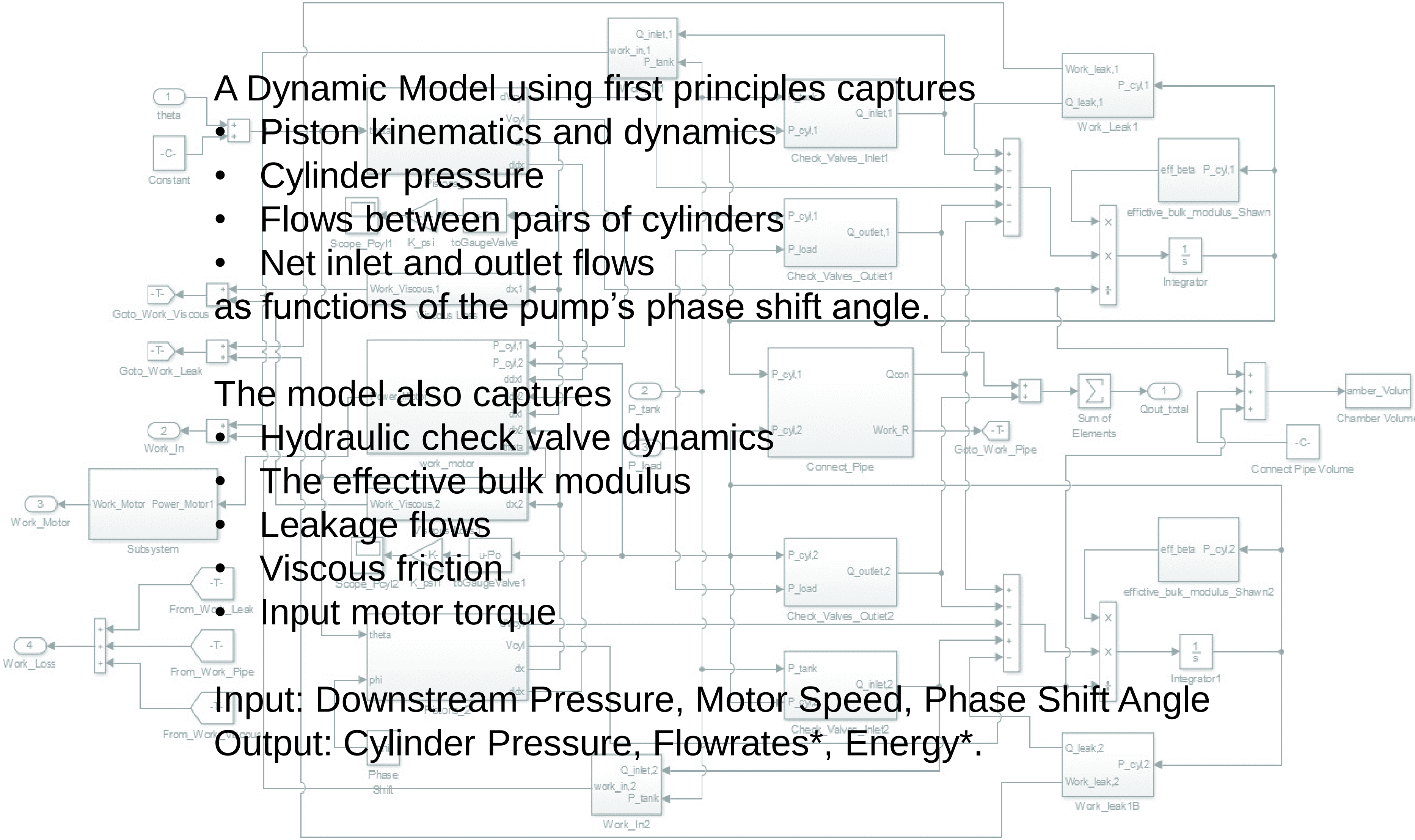
- Piston kinematics and dynamics
- Cylinder pressure
- Flows between pairs of cylinders
- Net inlet and outlet flows

as functions of the pump's phase shift angle.

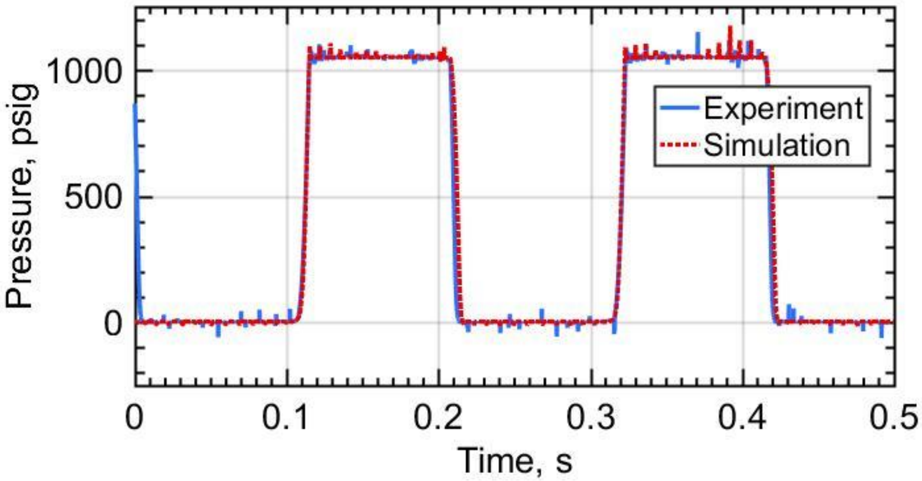
The model also captures

- Hydraulic check valve dynamics
- The effective bulk modulus
- Leakage flows
- Viscous friction
- Input motor torque

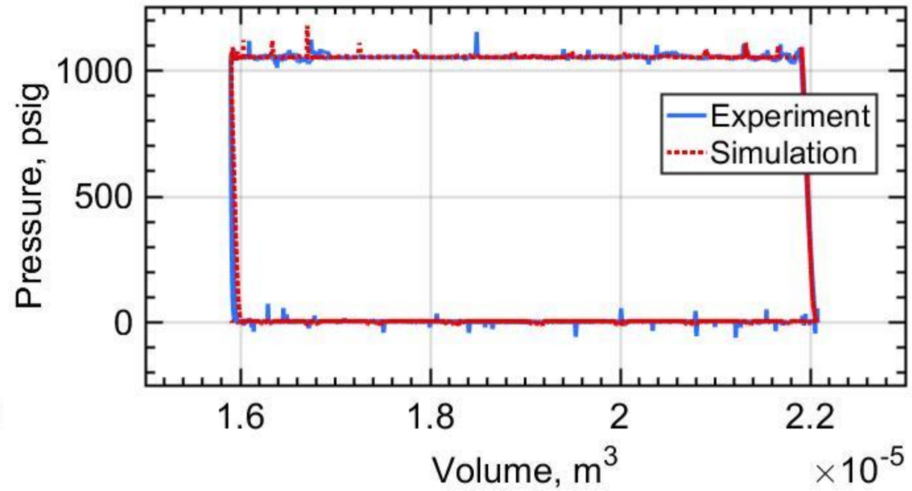
Input: Downstream Pressure, Motor Speed, Phase Shift Angle
Output: Cylinder Pressure, Flowrates*, Energy*.



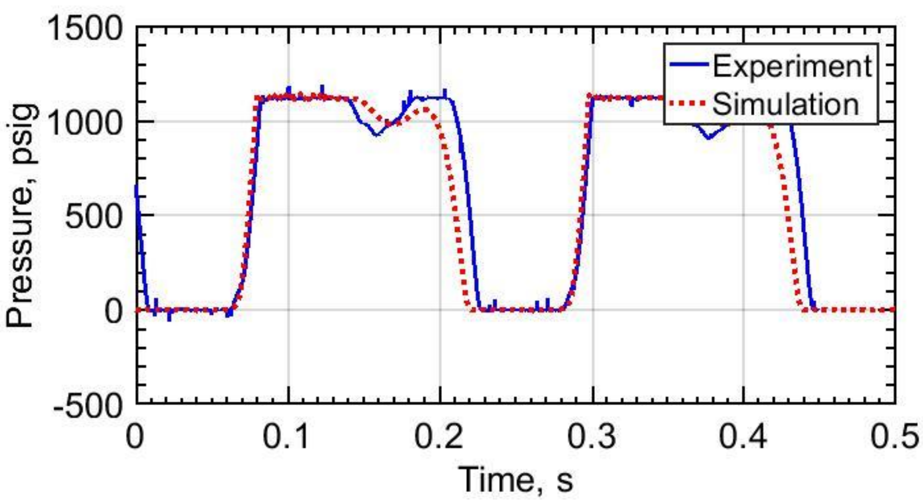
AFH VDP Model Validation



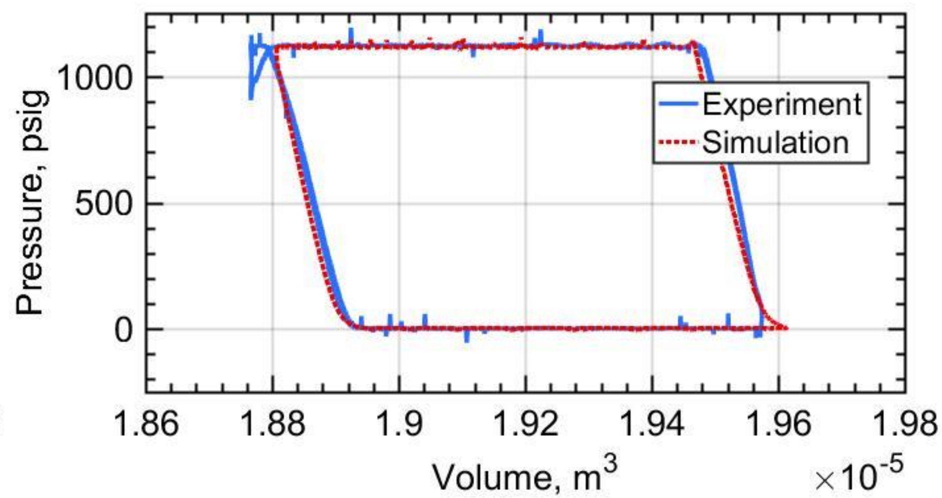
(a) $\phi = 2^o$, 250 rpm



(b) $\phi = 2^o$, 250 rpm

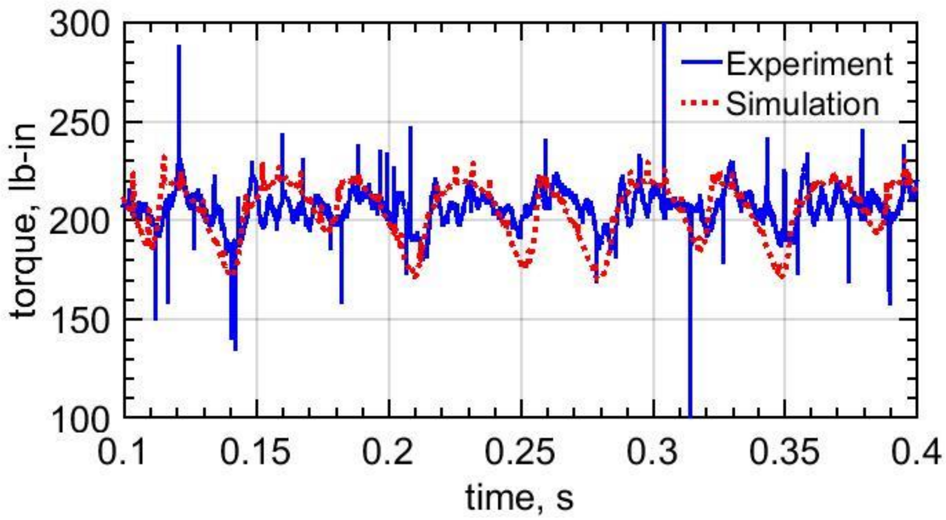


(c) $\phi = 165^o$, 250 rpm

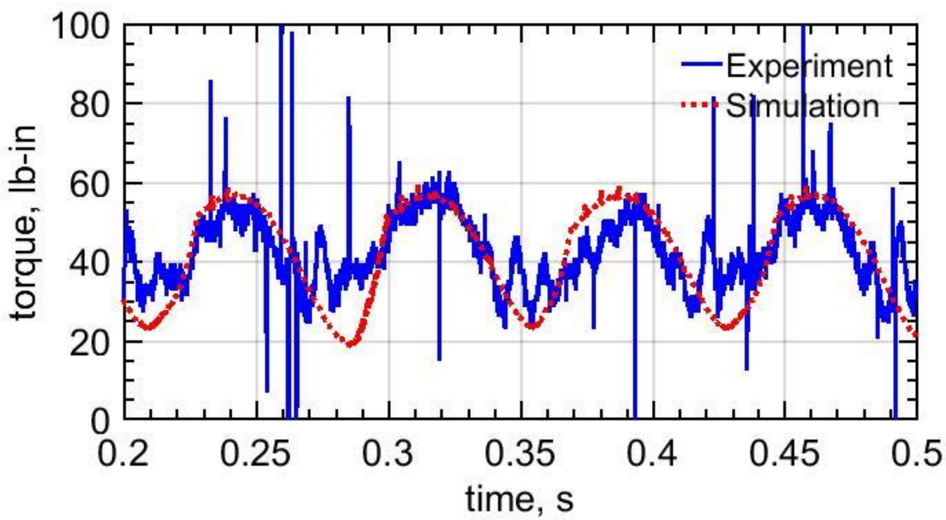


(d) $\phi = 165^o$, 250 rpm

AFH VDP Model Validation

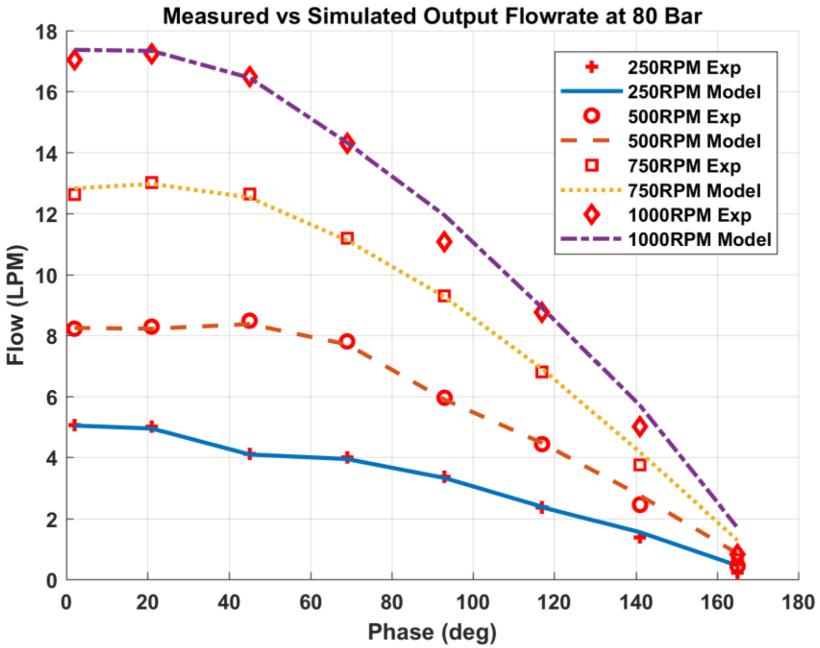


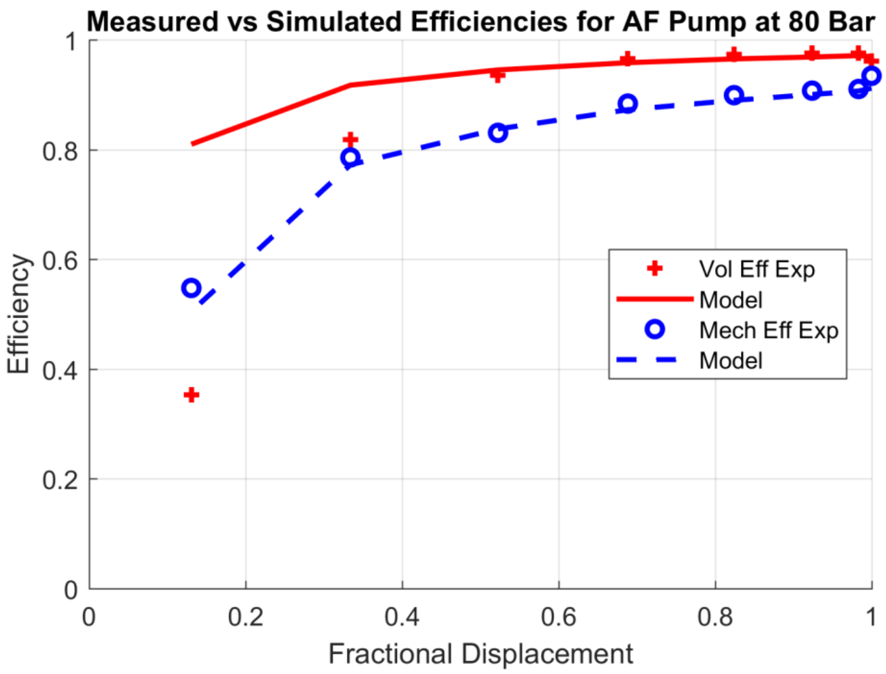
$\phi = 2^o$
250rpm
1000psi



$\phi = 165^o$
250rpm
1000psi

AFH VDP Model Validation

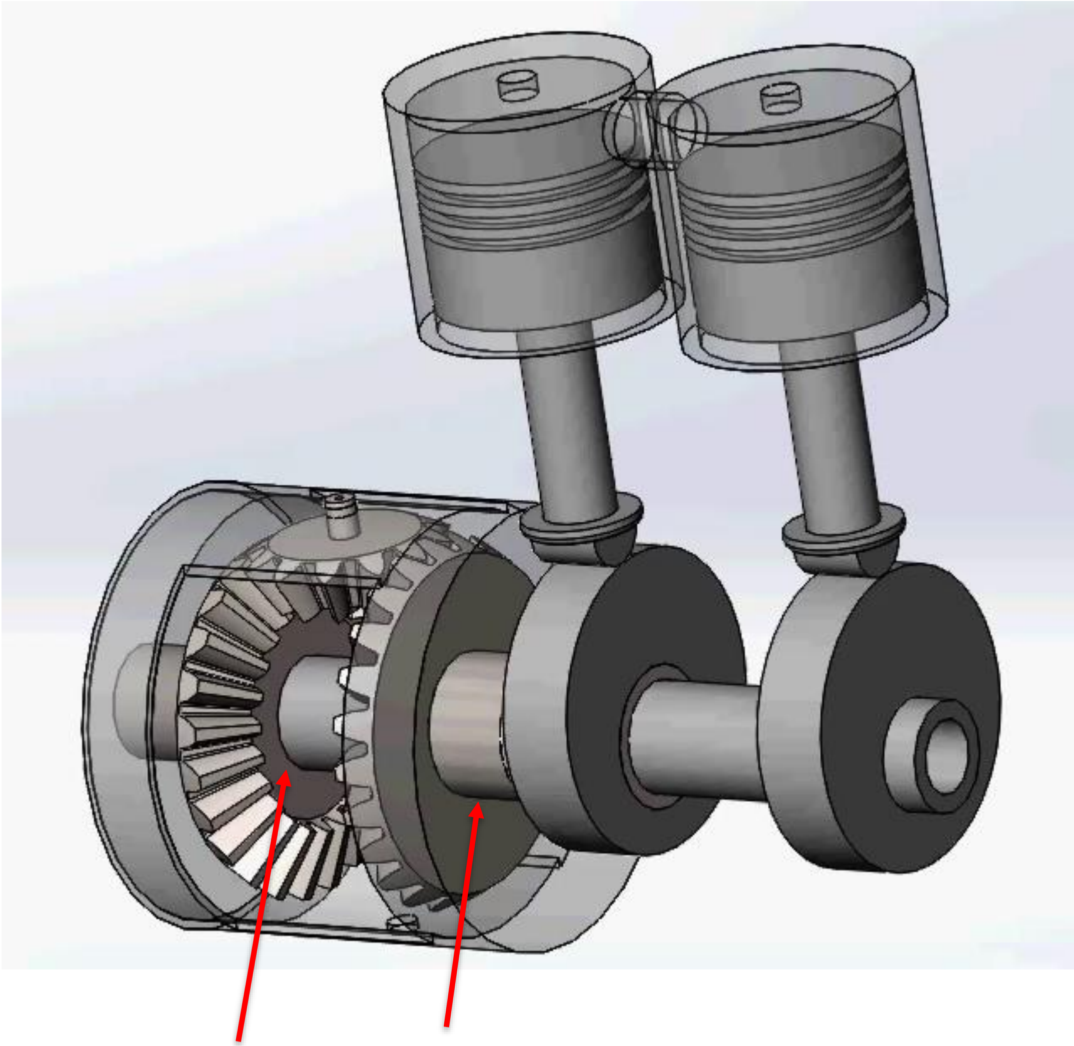




Results start to deviate from model due to large dead volume.

Large dead volume, viscous losses and friction in chain and seals.

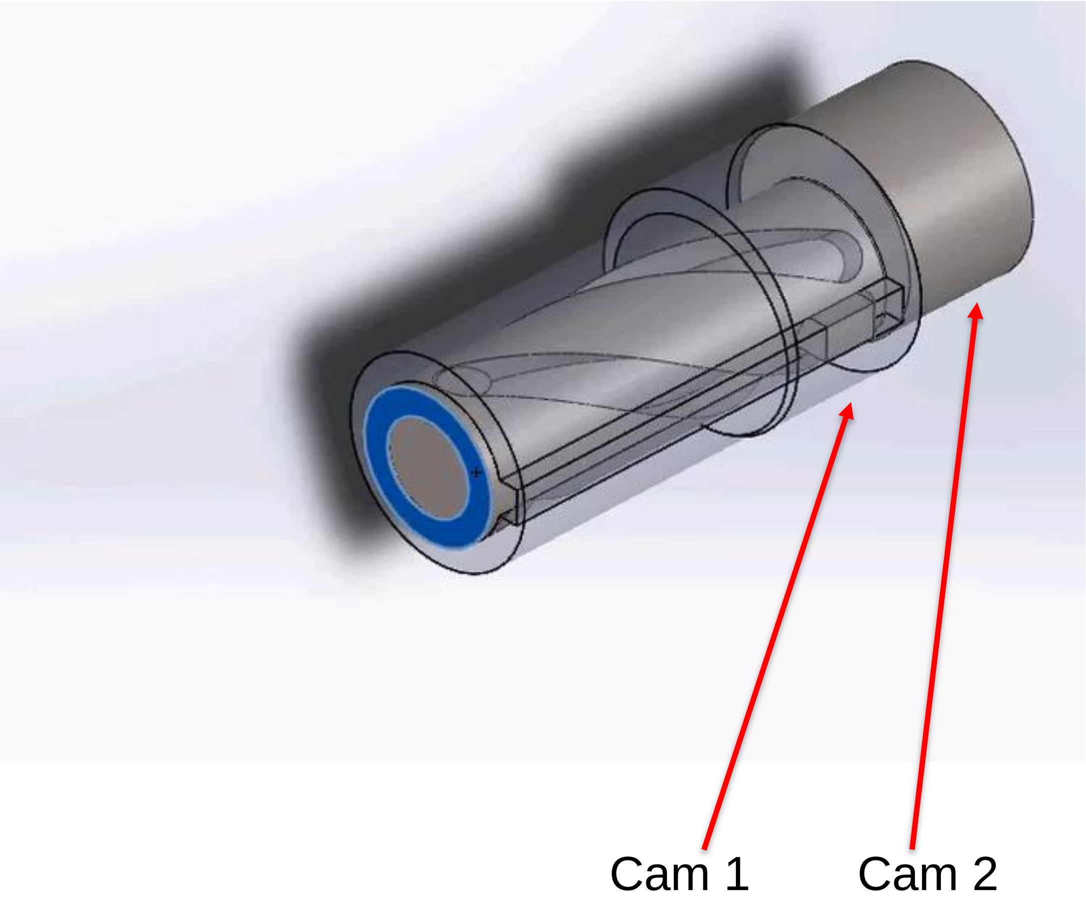
Phase Shift 1 – Differential Gear

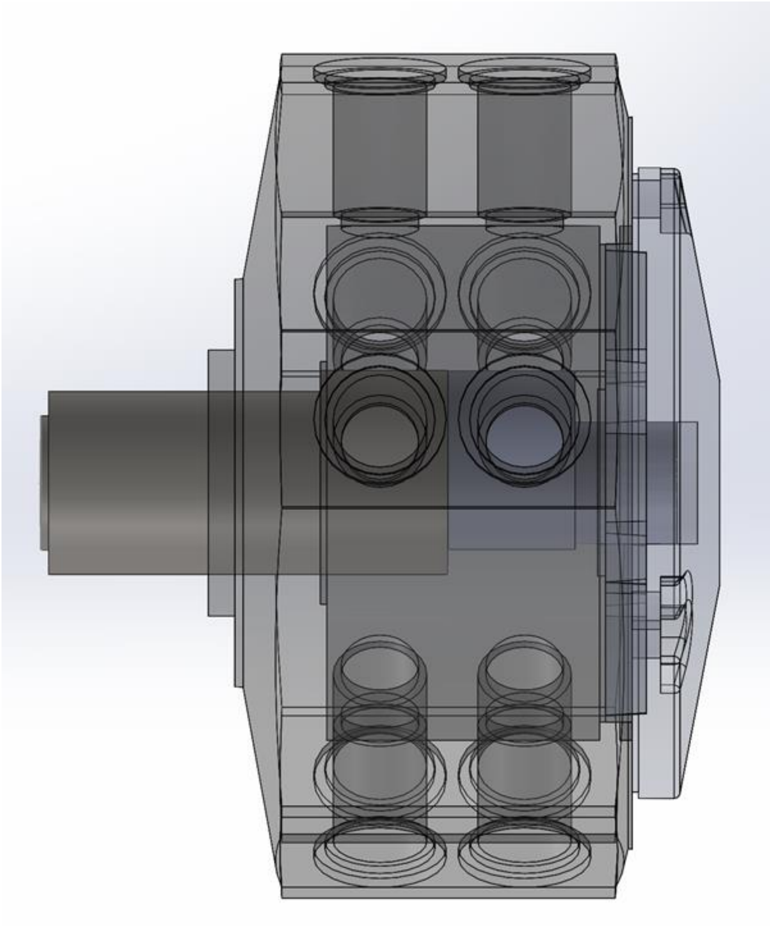


narrow long wide hollow

- One ***wide hollow*** shaft (to drive one cam) and one ***narrow long*** shaft (to drive the other cam).
- The differential gear set can be placed at one side of a radial piston pump, thus reducing the distance between two parallel pumping units and shortening the connecting pipe size.
- The whole size of this phase shift mechanism can be small. For illustration purpose, it is larger here.

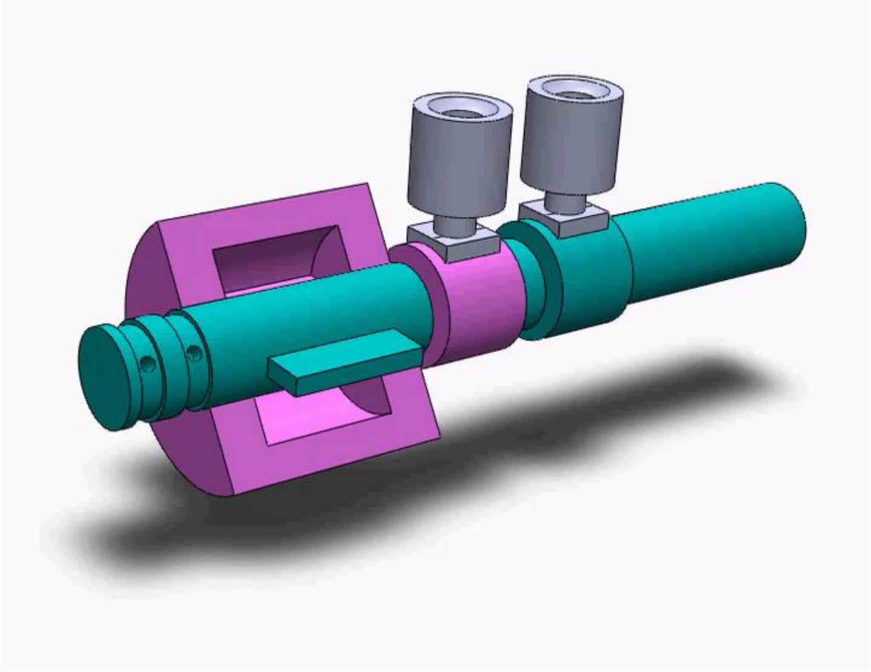
Phase Shift 2 – Pin in Slot



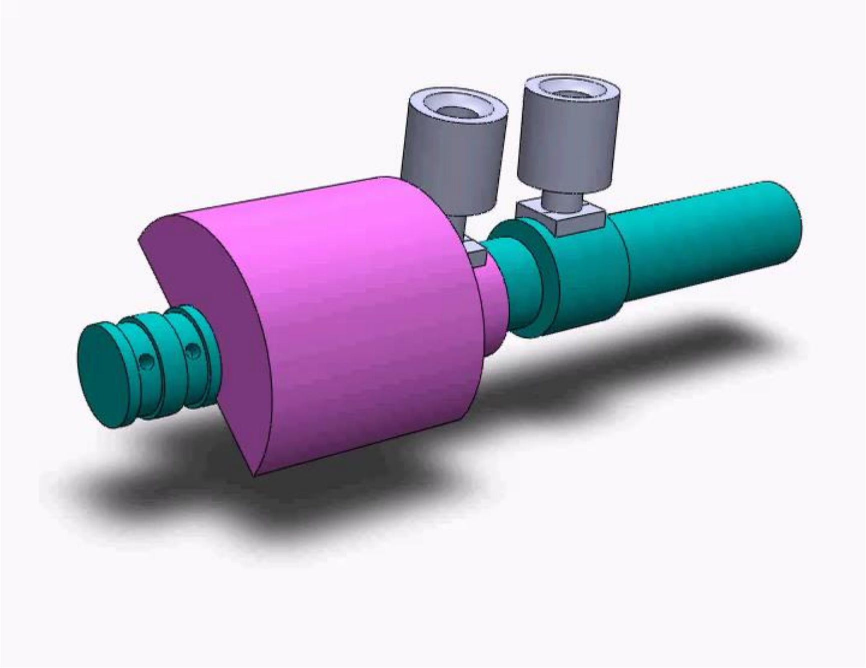


* Credits go to Caroline for her great work.

Phase Shift 3 – Toyota Phaser



In Phase



Out of Phase

Thank You!
Question?

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