INDUSTRIAL TRAINING REPORT

CATERPILLAR INDIA PRIVATE LIMITED

ORIFICE SIZING TOOL

A Study in Fluid Power Control

- Done By,

Gowtham V (ME11B023)

Third Year Undergraduate

Department Of Mechanical Engineering

IIT Madras

Mentored by,

Mr. Shashank Sharma

Engineer, Engineering Design Center India

CATERPILLAR INC.
Engineering Design Center India

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ACKNOWLEDGEMENT

I take this opportunity to thank Mr.Shashank Sharma, my mentor, the guidance and support of whom made completion of this project possible.

I would like to thank Mr. (Sr. Engineering Specialist-Design) for the valuable inputs given during the course of the project.

I would also like to thank Mr. Amit Lodaya, my team leader, to his sincere support and advice.

I thank Mr. Ranjit S.Sandhu and all the other employees of Caterpillar EDC India for extending their courtesy to work in their midst and for providing me with all the necessary information to make my stay comfortable.

I sincerely thank the management for granting me the opportunity to work at Caterpillar India Pvt. Ltd. as a Project Trainee and for providing me with all the resources that enabled me to gain a learning experience and professional skills.

COMPANY PROFILE

Caterpillar Inc., is an American corporation which designs, manufactures, markets and sells machinery and engines and sells financial products and insurance to customers via a worldwide dealer network.

Caterpillar is the world's leading manufacturer of construction and mining equipment, diesel and natural gas engines, industrial gas turbines and diesel-electric locomotives. With more than US $ 89 billion in assets, Caterpillar was ranked number one in its industry and number 44 overall in the 2009 Fortune 500.

Caterpillar has a list of 400 products for purchase through its dealer network. Caterpillar's line of machines range from tracked tractors to hydraulic excavators, backhoe loaders, motor graders, off-highway trucks, wheel loaders, agricultural tractors and locomotives.

Caterpillar machinery is used in the construction, road-building, mining, forestry, energy, transportation and material-handling industries. Caterpillar is the world's largest manufacturer of wheel loaders.

A portion of Caterpillar's business is in the manufacturing of diesel and natural gas engines and gas turbines which, in addition to their use in the company's own vehicles, are used as the prime movers in locomotives, semi-trucks, marine vessels and ships, as well as providing the power source for peak-load power plants and emergency generators.

The Caterpillar Electronics business unit has formed Caterpillar Trimble Control Technologies LLC (CTCT), a 50:50 joint venture with Trimble Navigation to develop electronic guidance and control products for earthmoving machines in the construction, mining and waste industries.

Caterpillar products and components are manufactured in 110 facilities worldwide. 51 plants are located in the United States and 59 overseas plants are located in Australia, Belgium, Brazil, Canada, China, Czech Republic, England, France, Germany, Hungary, India, Indonesia, Italy, Japan, Mexico, the Netherlands, Northern Ireland, Poland, Russia, Singapore, South Africa and Sweden.

In 2012, Caterpillar Inc. was named to the Dow Jones Sustainability Indexes (DJSI) for the twelfth straight year, recognized as one of the sustainability leaders in the Industrial Engineering sector.

In June 2010, Caterpillar Motoren, the manufacturing arm focused on the production of MaK and Cat engines for marine, petroleum and power generation applications, was awarded an Environmental Award from the Economic Association of Schleswig-Holstein, Germany as recognition for its enormous efforts in reducing energy consumption, resource reduction and elimination of greenhouse emissions through the manufacturing process.

Caterpillar has been active in India since the 1930s. Caterpillar manufactures 60 and 100-ton off highway trucks (OHT) in India for the domestic and export markets. Cat reciprocating engines and solar turbines, enable gas compression for key customers including Reliance, ONGC, British Gas, CAIRN India and OIL India.

Hoist Mechanism Overview

Image 1: Hydraulic Hoist mechanism

(*Source: www.thenex.com/.../multi-stage-telescopic-conveyor.html*

Application of hoist mechanism in trucks using telescoping hydraulic cylinder is very common. The system requirement is to load and unload cargo of about 100 tons, which when loaded must also be transported.

The cargo is lifted by two hydraulic cylinders in two corners of the truck, and are powered by a common pump.

This hoist mechanism is one of the implements in the truck's hydraulic system, whose primary purpose is to control the steering mechanism. There are multiple implements in the truck hydraulic system, including brake cooling, and multiple pumps with different capacities are utilized in the same.

Cycle Time:

It is defined as the time for the complete operation, either raising or lowering to complete. It can also be defined as the time for complete stroke of cylinder to extend or retract respectively.

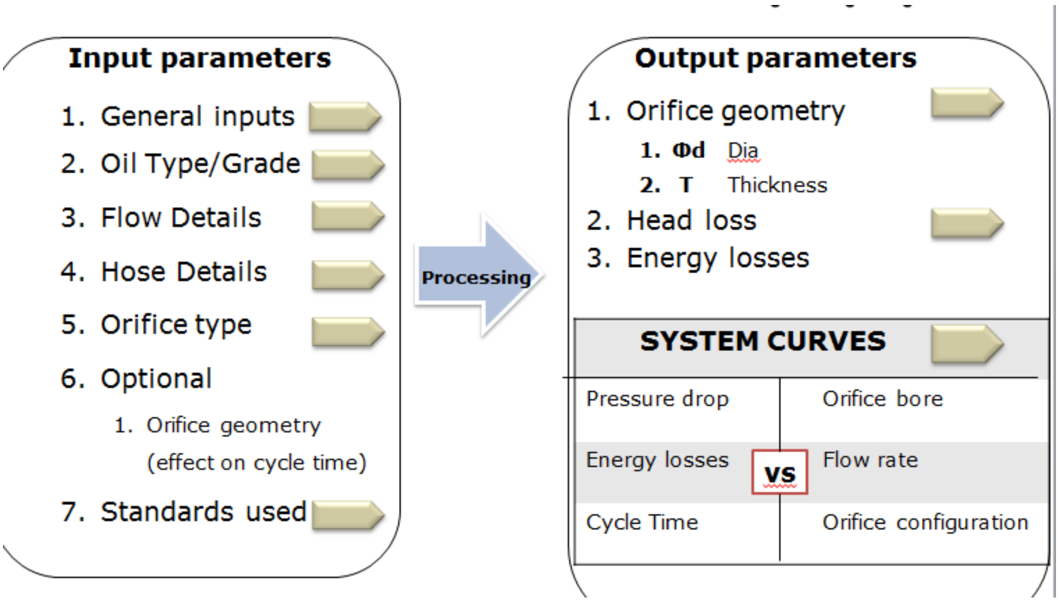
Project objective

Cycle time for forward and reverse operation of the cargo loading arrangement are required to be equal. For varying orifice size and flow requirements, a software tool is to be created to design the orifice plate, and to generate performance curves including that of system efficiency based on input parameters: flow, oil type, diameter, and pressure drop.

1. Selection of optimum sized Orifice Plate and to calculate
    1. Flow Regime(Laminar/Turbulent)
    2. Pressure loss
    3. Energy Loss
2. Orifice plates in series and parallel: effective resistance
3. Curves regarding Orifice Plate

Output Parameter		Variable
Pressure Loss		Orifice Throat Dia
Discharge coefficient	VS	Cycle Time
Energy Losses		

1. INPUT OUTPUT REQUIREMENTS



2. RESTRICTION ORIFICE: AN INTRODUCTION

Restriction orifice (RO) is mainly used to achieve controlled or restricted flow of process medium. The orifice offers a restriction to the process flow and the pressure head drops from the upstream to the downstream. The permanent pressure loss by the device is the intended pressure drop for which it is sized. The area of the orifice determines the rate of flow at the outlet of a given process fluid for the specified pressure and temperature.

Plate thickness is decided based on bending stress and other considerations.

Orifice Plates are generally used for flow meter applications. Orifices are commonly found within pipelines as flow-restricting devices, in perforated pipe distributing and return manifolds, and in perforated plates. They are a class of differential producing devices.

The velocity of approach term [1 − (*Ao* /*A*)2] accounts for the kinetic energy approaching the orifice, while the orifice coefficient or discharge coefficient *Cd* accounts for the vena contracta effect which causes the fluid to accelerate to velocity greater than *Q*/*Ao* . Downstream of the vena contracta, the velocity decelerates and some pressure recovery may be expected. Any pressure recovery is completed about 4 to 8 pipe diameters downstream of the orifice.

The orifice coefficient has a value of about 0.62 at large Reynolds numbers (Re = $\rho VD/\mu$ > 20,000), although values ranging from 0.60 to 0.70 are frequently used. At lower Reynolds numbers, the orifice coefficient varies with both Re and with the area or diameter ratio.

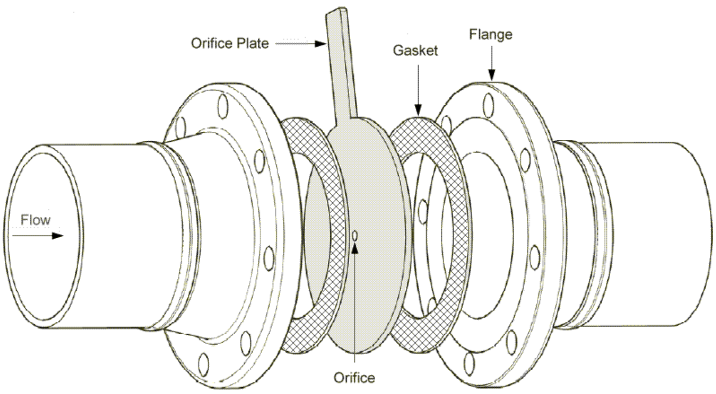


Image 2: SampleOrifice Plate Fitting in a pipe (Resource: wermac.org)

3. APPLICATION OF RESTRICTION ORIFICES

1. Restriction Orifice (RO) to check excess flow.

ROs are used to restrict the excessive flow in case of a rupture. Thus in Well head applications if the down holes valves to be closed due to fire, the hydraulic power oil to the valve actuator is depressurized by the use of fusible plug which fuses and allows the hydraulic oil to leak through a RO at a restricted flow rate.

2. Restriction Orifice (RO) in pump recirculation line.

ROs are also used in centrifugal pump's recirculation line where a constant recirculation flow is required and control of recirculation and forward flow rate is not important. The recirculation ensures that cavitation / starvation cannot happen in the pump

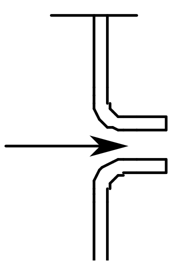
3. Restriction Orifice (RO) for controlled pressurization.

During the start-up of a process plant, many plant sections are required to be pressurized with the incoming process fluid in controlled manner. This is because the upstream section will be usually at a much higher pressure than the downstream. Thus if there is no restriction on the flow rate, the initial flow rate may be very high and may damage the pipe line and equipment. ROs are used for gradual pressurization. To restrict the flow the ideal condition is to design for the choked flow for gas. As during the choked flow, the rate of flow will be less as it will be proportional to the square root of inlet pressure rather than to the differential pressure.

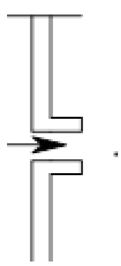
4. Miscellaneous:

It has multiple applications from protecting sensitive equipment from time-varying peak flows in drainage systems, to controlling flow output using variable diameter orifice restrictions to change flow for a constant displacement input flow.

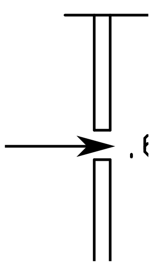
4. CONFIGURATIONS OF ORIFICE PLATES



Round edged Orifice



Square edged Orifice



Thin plate orifice

Configuration studied in project: <u>Sharp-edged orifice plate</u>

Factors involved

There are various factors involved in selection and design of an orifice plate for a required system condition, including and not limited to: material of plate (316 steel being the most common), type of boring of the orifice hole (including concentric, eccentric, counter-bored, and size and thickness of plate.

The thickness of the plate used is a function of the line size, the process temperature, the pressure, process fluid and the differential pressure. There are various orifice fitting techniques available to introduce the orifice plate in a line. There is a measurable pressure drop across the orifice plate, which is a function of the orifice plate parameters, and flow metrics.

Energy losses, and hence impact on the system efficiency curves due to the orifice plate can also be estimated in terms of input parameters. The crucial impact on the system is the pressure drop due to the orifice plate.

In the design of orifice plates, selection of the system fluid impacts the various performance characteristics. Oil is selected from a variety of grades, and temperature effects like change in viscosity and density during operation are to be considered. System energy losses also depend on these factors, and hence the system is required to design orifice plate for the system for any required oil used for the overall system. Also temperature effects on orifice plate dimensions may need to be considered.

Project Deliverables:

- Software tool that
  - Is user-friendly and requires minimal inputs
  - Recommends best orifice size and type
  - Provides options for different orifice configurations
  - Is a generalized tool to get orifice size for any application
  - Cycle time vs. orifice plate bore size
- Performance curves:
  - Cycle time relation to Orifice Diameter
  - Losses/Efficiency vs. orifice Diameter
  - Relative performance curves: different configurations
- Application in field testing, fast processing and user-friendly software.
- Ease for usage even without extensive design knowledge for orifice selection.
- Can integrate with analysis of other systems also in future(Pump, Valves)
- Optimum solution considering different orifice types and sizes
- Interactive GUI with dynamic output with option(like slider) for varying specs and get visual outputs and plots

Orifice Plate Pressure Loss

1. BERNOULLI SIMPLIFIED APPROACH

Using the Bernoulli equation for the orifice plate problem is wrong, but it can give a simplified approach for quick calculations.

Bernoulli equation is not valid due to the following reasons:

1. Irrotational assumption: Flow is mostly turbulent in the given flow regime, and hence losses are underestimated.
2. Viscous effects and recirculation region developed.

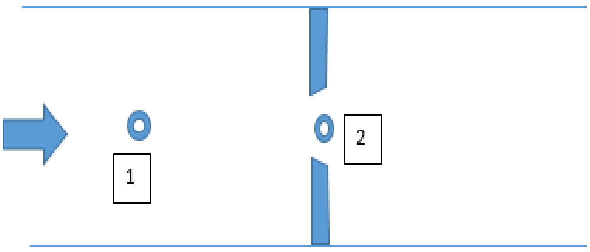


Image 4: Orifice plate in a pipe

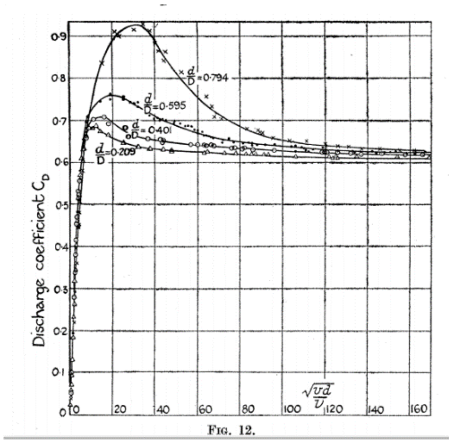


Image 5: C_d vs √Re plot(Source: [4])

For a preliminary analysis, as the flow is incompressible, points 1, 2in the pipe flow, clearly in the same streamline, are considered. Inviscid assumption is not valid.

Using Bernoulli's equation, considering flow input Q, between points 1, 2, 3 in the same streamline.

$$P_1 + \rho * \frac{Q^2}{A_1^2} = P_2 + \rho * \frac{Q^2}{A_2^2}$$

On solving,

$$Q = C_d A_2 \sqrt{\left(\frac{1}{1-\beta^4}\right)} \; \sqrt{\left(2 * \frac{\Delta P}{\rho}\right]}$$

Equation (1)

Where $\Delta P = P_2 - P_1$ and $\beta = {Orifice\ Diameter}/{Hose\ Diameter}$

Here C_d is the discharge coefficient of the orifice, depends on Reynolds number of flow, and diameter ratio.

We now discuss the most common application, orifice plate flow meter.

Pressure Tappings in Flow meters

Pressure probes can be placed at various positions along the pipe length based on convenience and accuracy required in flow calculations. Each have a different coefficient of discharge relation, and different accuracy

Type of pressure tappings, for flow meter applications:

1. **Corner tappings** :
   Immediately upstream and downstream of the plate
2. **D and D/2 taps**
   Pressure at given distance upstream and downstream respectively
3. **Flange taps**:
   Placed 1 inch upstream and downstream of the plate'
4. **Vena contracta taps**:
   Probes placed at point of minimum pressure, the vena contracta, explained below.

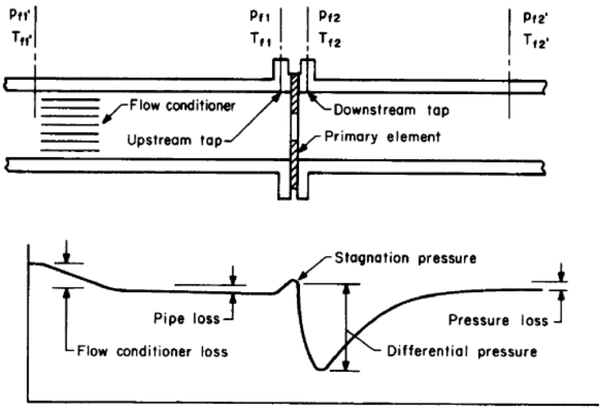


Image 6: Flow meter application, and pressure variation across length

3. VENA CONTRACTA

The real flow through an orifice plate converges to a smaller diameter than the orifice bore, at a point in the center line of the pipe called the vena contracta. Many flow-meter designs target at finding pressure at the vena contracta for computation.

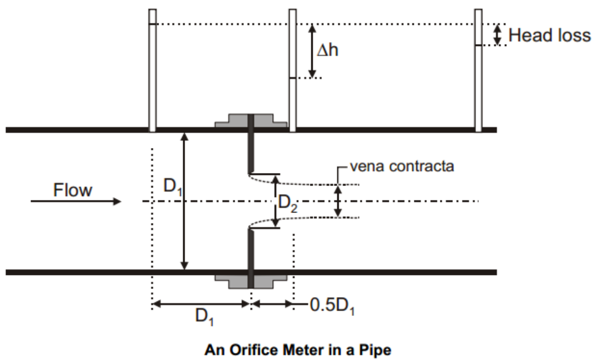


Image 7: Vena Contracta in Pipe (*Resource: ocw.usu.edu)*

Sample images of Orifice Plate

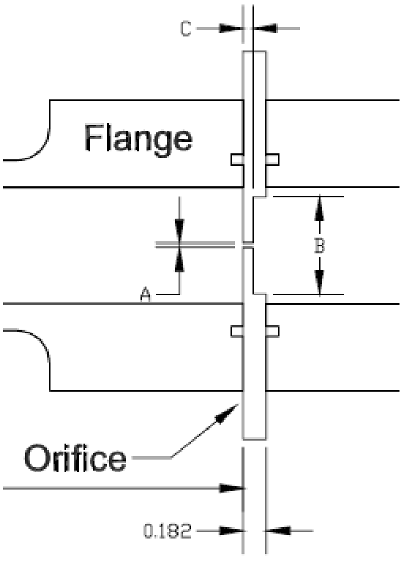


Image 8: Sample orifice plate fit in pipe flow

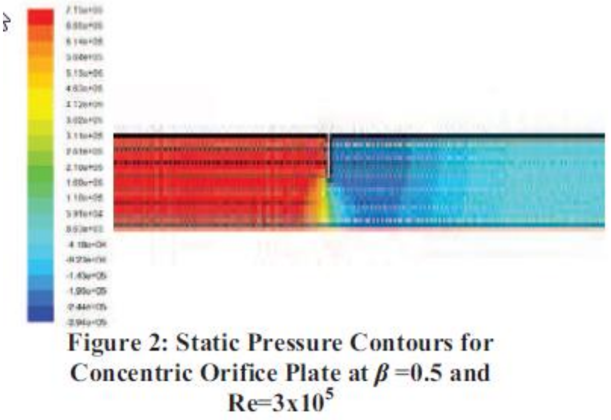


Image 9: Pressure contours in flow simulation of orifice plate(Source:[8])

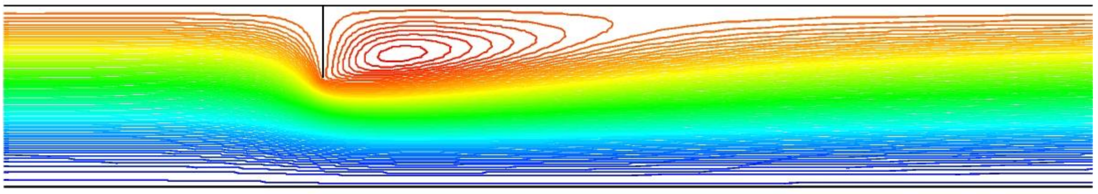


Image 10: Stream lines in turbulent flow simulation of orifice plate(Source:[8])

Standards used – ANSI 5167-1 and ANSI 5167-2

Final relation used: $Q/A = C_d/\sqrt{1-\beta^4}\ \sqrt{2*(\frac{\Delta P}{w})/\rho}$

Here w = pressure recovery ratio, given in the standards (cannot be replicated).

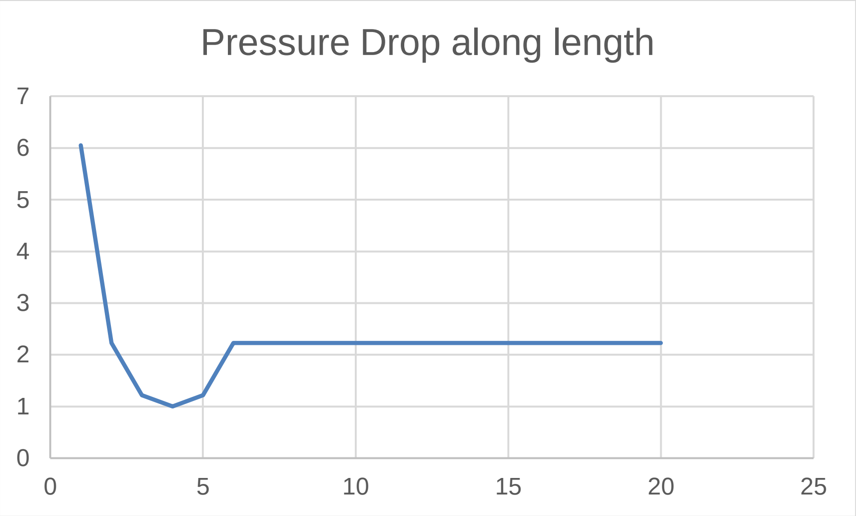


Image 11: Pressure recovery factor sample graph

Or, Permanent pressure loss: = $w * P$, P is pressure drop across orifice.

Limitations:

- Diameter Ratio 0.1 < β < 0.75
- Plate thickness(bidirectional) 0.005 D< E < 0.02 D
- Pipe ID D: 50 mm < D < 1000 mm
- Maximum pipe roughness (Ra/D) given by $15*10^{-4}$
- Orifice diameter d > 12.5 mm

Standards permit diameter ratio of d/D = 0.1 to 0.75 only.

Labelled Sample Circuit under Analysis

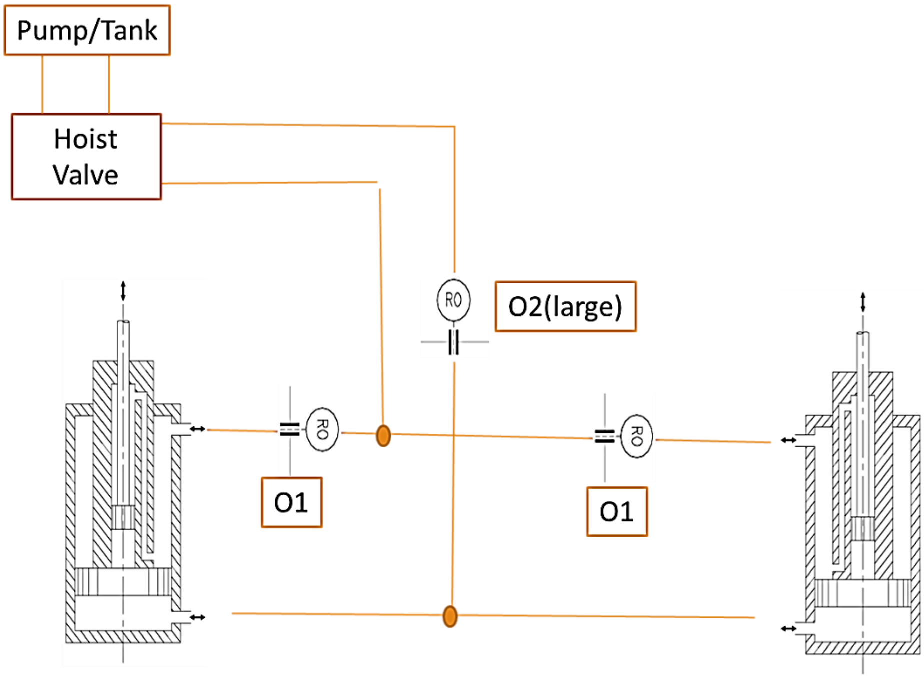


Image 12: Sketch of sample hydraulic circuit under study

Description:

A constant displacement pump is connect to a spool valve, a hoist valve, a supplies flow to two hydraulic cylinders used for hoist operation.

Operations:

1. Raise Operation:
    a. Hoist valve directs supply flow to bore end of both telescopic cylinders
    b. Cylinder extension occurs.
    c. As there are two stages, stage 2 force is significantly lower
2. Lower Operation
    a. Hoist valve directs supply flow to bore end of both telescopic cylinders
    b. Cylinder extension occurs.
    c. As there are two stages, stage 2 force is significantly lower
3. Snub Operation(Not studied)
    a. When the cargo is lowered, is about the hit the base, speed is significantly reduced, and slowly stopped.

Components Description

1. GEAR PUMP

It is one of the most commonly used rotary positive displacement pumps in hydraulic circuits. As a positive displacement pump, if forces fluid to move by trapping a fixed amount and forcing (displacing) that trapped volume into the discharge pipe. Supply end is connected to a tank.

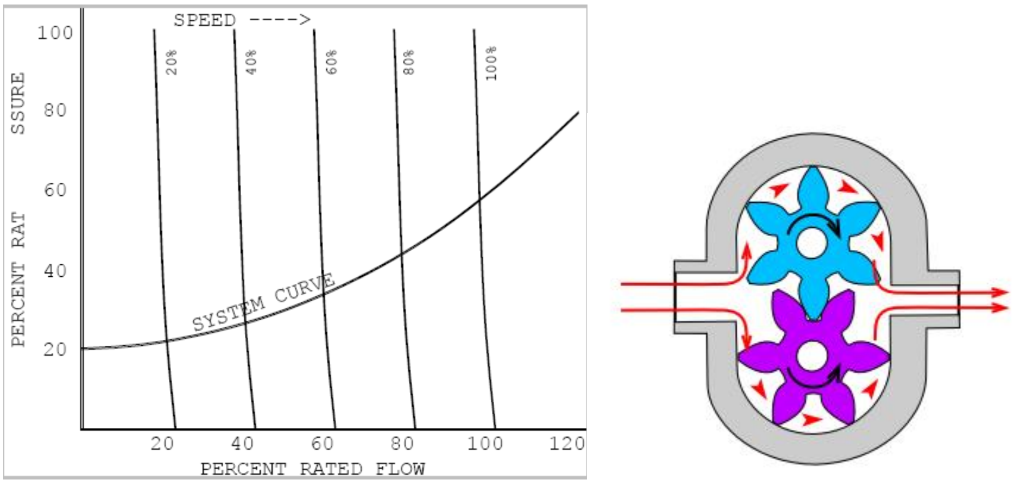


Image 13: Gear pump schematic(Source: Gear pump, Wikipedia.org)

Each revolution, it forces a fixed amount of flow. Hence, it is usually powered by a variable speed motor drive. If N is the motor speed (in RPM), then as clearly seen in image <> ,output flow increases linearly with motor drive speed.

Also, pump output flow is independent on load pressure, as in a centrifugal pump, thus cannot be throttle controlled. Yet, the characteristic curve is sometimes inclined, due to leakage losses.

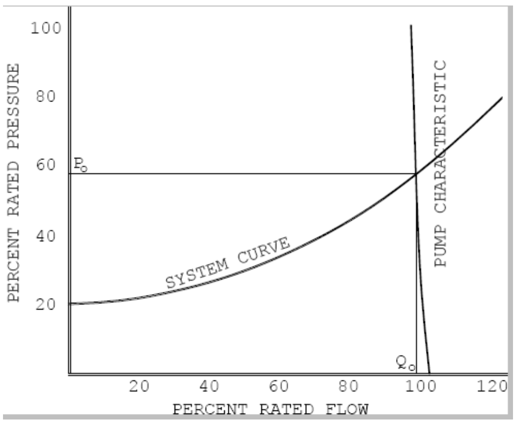


Image 14: Characteristic curve of gear pump (Source: [14])

Displacement = *Cubic Inches (cc) per Revolution of drive shaft*

Flow = *Displacement X Shaft Speed X Volumetric Efficiency*

2. PRESSURE RELIEF VALVE

Pressure-relief valves limit the maximum pressure in a hydraulic circuit by providing an alternate path for fluid flow when the pressure reaches a preset level.

There are two-types of relief valves: direct and pilot operated.

Seen below is a simple sketch of the same.

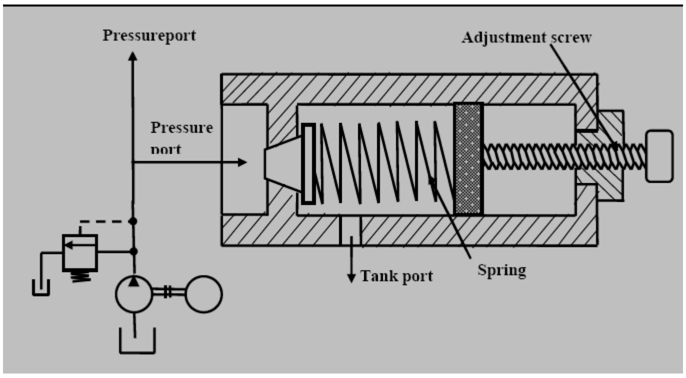


Image 14: PRV(source: NPTEL fluid power control)

The adjustment screw is used to adjust the pressure relief valve setting. The drain is directly sent to tank, and energy is wasted.

Applications:

1. Limiting maximum system pressure at a safe level
2. Fixed-volume pump circuits require a relief valve to protect the system from excess pressure.
3. Also for pressure control flow manipulation to implements, at the cost of wasted energy.

Use of relief valve with gear pump

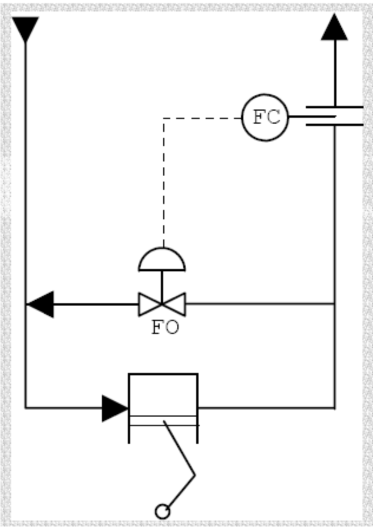


Image 15: Recycle Control(source: [14])

5. PRESSURE COMPENSATED PUMP

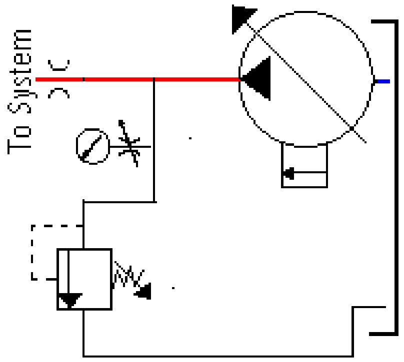


Image 16, Pressure Compensated pump(Source: [11])

Pressure compensated Pump will provide full pump flow at pressures below the compensator setting. Once the pump flow is restricted, pressure will build up to the setting of the compensator and then the pump will de-stroke to the level needed to maintain the compensator pressure setting.

Below pressure settings, flow is maximum. Once reached, pump de-strokes to provide flow required to maintain set pressure. Pump will maintain maximum pressure till system pressure drops.

Note: Above is applicable only to variable displacement pumps. For constant displacement pumps, such systems are not possible, so pump flow must be as close to implement flow as possible to reduce losses.

6. SPEED CONTROL

Speed control is an obvious method of controlling the flow rate of PD pumps since flow is essentially proportional to speed.

Variable-frequency drive (VFD) (also termed adjustable-frequency drive, variable-speed drive, AC drive,micro drive or inverter drive) is a type of adjustable-speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage. Many fixed-speed motor load applications that are supplied direct from AC line power can save energy when they are operated at variable-speed, by means of VFD.

. The large inertia of the system means that speed changes cannot be made quickly.

7. RECYCLE CONTROL

Once an implement is fit with a pressure relief valve, it sets maximum implement pressure, and hence discharge pressure of pump, and protects the pump.

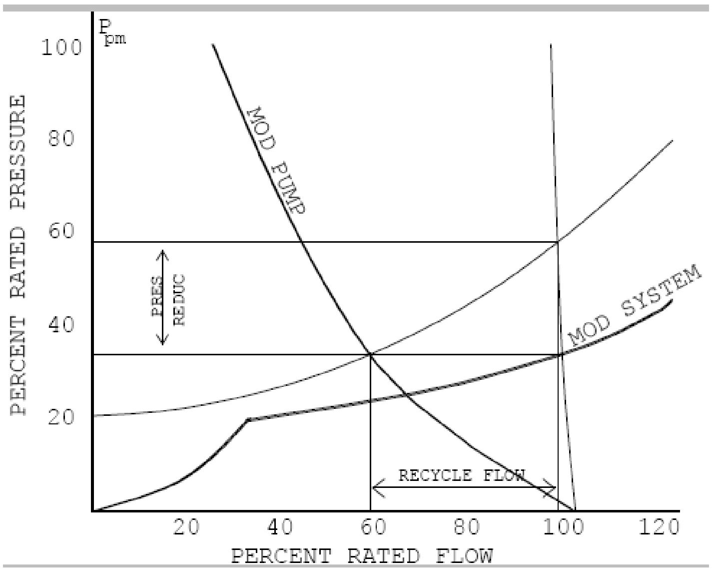


Image 17: Implement flow modification with load pressure (Source: [14])

A pressure relief valve, **fail open** is installed in a line teeing off from the discharge and leading back to the source of the liquid, possibly a surge tank.

The flow through the pump is essentially as before but the pressure to the process has been reduced. Process flow will, of course, also be reduced by the amount flowing through the recycle line, hence achieving required flow to system.

Losses:

1. Slippage losses:

   These are losses induced because of the recycle flow from the pressure relief valve, due to excess load pressure in the system.

   Let implement flow = $\mathbf{Q_{implement}}$, Relief valve setting = P.

   Slippage Losses **= P*($\mathbf{Q_{pump}}$ - $\mathbf{Q_{implement}}$)**

   Slippage losses are inevitable. The required cycle time fixes the implement flow, and pump flow can be varied to a limit with motor speed. Hence, slippage losses are modeled.

2. Throttle Losses:

   These losses occur when multiple loads requiring different pressures are connected in series, and the pump hence supplies peak pressure to both implements at common supply end.

Hence, the second valve throttles the flow to produce required pressure at implement. Here, this is not studied, as only one implement is connected.

8. HYDRAULIC CYLINDER

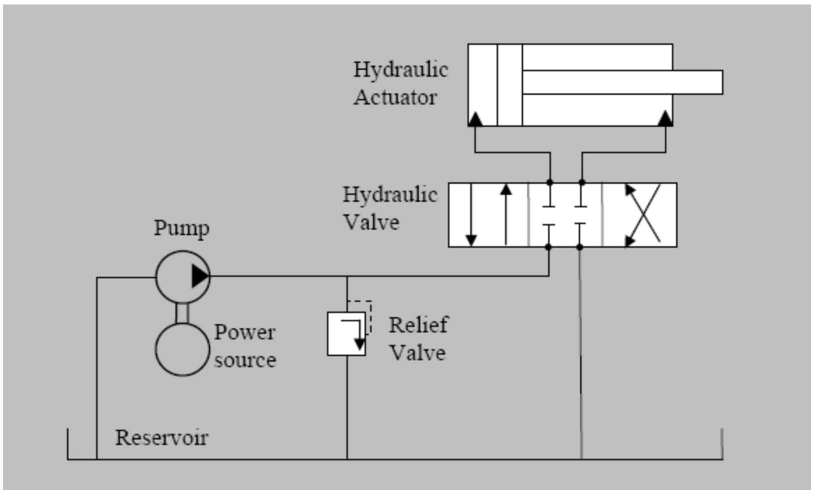
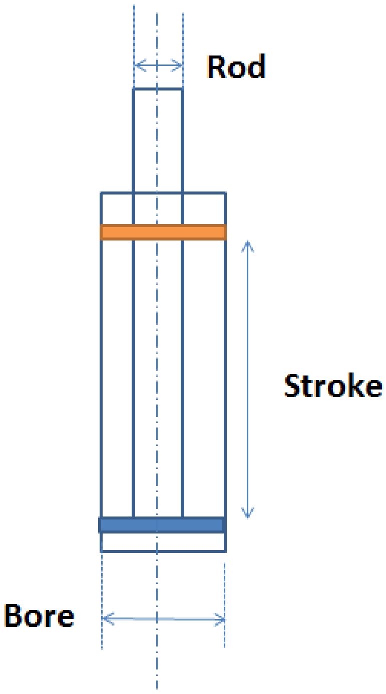


Figure 2-1 Conventional Valve Controlled Hydraulic Circuit

Source: NPTEL

It is the most common hydraulic actuator, used in rams, for linear actuation. Hydraulic cylinders get their power from pressurized hydraulic fluid, which is typically oil.



The hydraulic cylinder consists of a cylinder barrel, in which a piston connected to a piston rod actuates a load. Many types exist depending on load requirement, and speed requirements.

Types of cylinders:

1. Single-acting cylinders.
2. Double-acting cylinders.
3. Telescopic cylinders.
4. Tandem cylinders

In closed center systems, double-acting, telescopic cylinders are most commonly used.

Single-acting cylinders are used when load needs to be actuated in one direction, and in the other direction, either gravity or spring effect automatically brings load back. It consists of a piston inside a cylindrical housing called barrel. On one end of the piston there is a rod, which can reciprocate**.** At the opposite end, there is a port for the entrance and exit of oil.

Double acting cylinders have oil entry on one side, but internally redirected for supply and drain to tank.

Cylinder Friction factor:

Commonly, cylinder friction cannot be avoided despite lubrication.

Hence, entire fluid pressure force on the respective area, removing backpressure effects, is not transferred to load. It is complicated to model the friction factor effects etc. so as an industrial standard, a factor β is defined as

$$\beta = {(Actual\ Fluid\ Force)}\big/{(Theoretical\ pressure\ Force)}$$

From experimental and catalogue data, it is found to be close to a value 0.8. In general friction coefficient varies with pressures etc. and is a complicated phenomenon.

Image: Force Velocity Envelope (Source: http://hydraulicspneumatics.com/)

Above given a sample force-velocity envelope for a hydraulic cylinder, where the flow is controlled by a valve, and envelopes defined by cavitation considerations, and maximum supply pressure considerations.

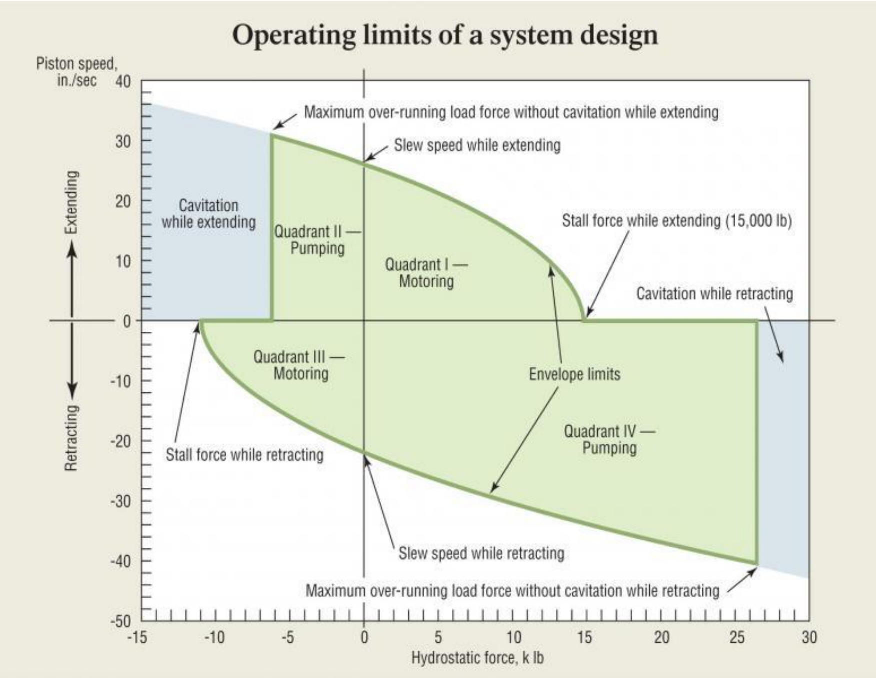


Image 18: Operating envelope of a hydraulic cylinder

(Source: [12])

Stall Force: At some load, the supply pressure can just lift the load, called stall force.

They are different for retraction and extension stroke. Slew speed is the speed of actuator motion at zero load. Hence the entire double-acting cylinder dynamics is studied.

6. TELESCOPIC CYLINDER APPLICATIONS

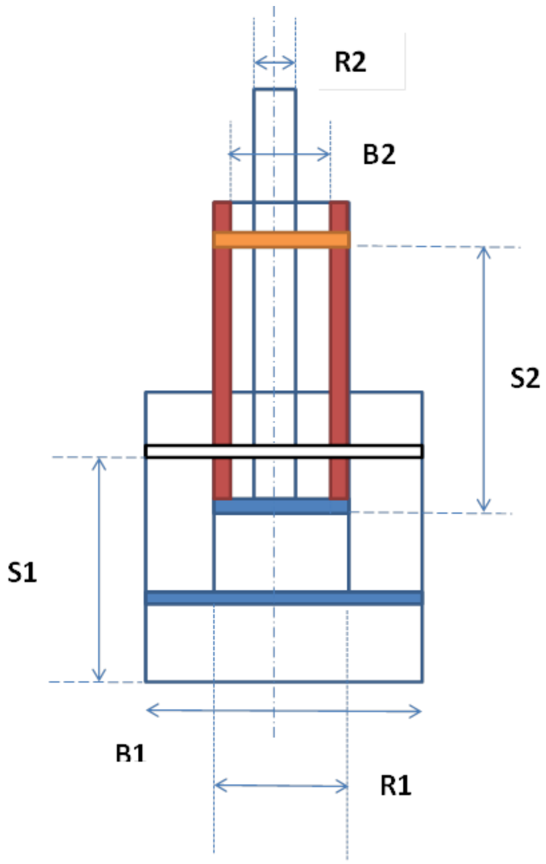


Image 17: Telescopic cylinder important dimensions

Telescopic cylinders exceptionally long output travel from a very compact retracted length. Typically the collapsed length of a telescopic cylinder is 20 to 40% of the fully extended length depending on the number of stages. As in a truck hoist system, space is limited, and the cargo must be tilted by a significant angle for dumping with appropriate speed, overcoming friction, it is required to use a telescopic cylinder. Here we analyse a 2 stage telescopic cylinder with 4 parameters:

1. Stage 1
   a. Bore Diameter A_{b1}
   b. Rod Diameter A_{r1}
   c. Area Ratio: A^{1}_{RP}, a crucial parameter, the ratio of areas in the rod side to the bore side.
2. Stage 2
   a. Bore Diameter A_{b2}
   b. Rod Diameter A_{r2}

c. Area Ratio: A^2_{RP}, a crucial parameter, the ratio of areas in the rod side to the bore side.

Dynamics:

Applied tensile force (when supply end is rod-side) = F_{retr}

Applied push force (when supply end is bore-side) = F_{ext}

Thus, when a telescopic cylinder is supplied with constant input flow Q, and supply pressure P

Stage 1 :

$F_{ext} = P*A_{b2}$

Extension speed $v = Q / A_{b2}$

Similarly for stage 2, hence maximum force is applied in the initial stage(1), and the force reduces in stage 2. This factor is not an issue for hoisting a truck bed, as after the completion of stage 1, the load is already at an angle, and requires lesser force to be lifted due to angle effects.

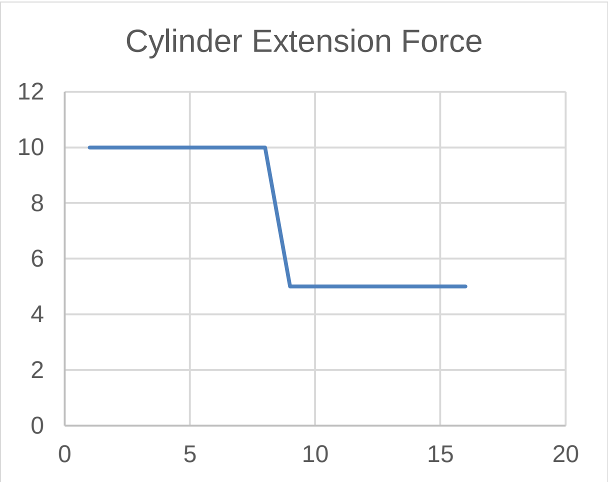


Image 18: Sample Extension Force Diagram – 2 stage telescopic cylinder

For retraction stroke, there are two designs of telescopic cylinders

1. Retraction force is constant throughout both stages.
2. Retraction force is area dependent as in extension.

Here type 2 is used.

Stage 2:

Retraction velocity = Q / A_{r2}

Similarly for Stage 1.

Drain Flow:

Another important consideration, as orifice plates are fitted on both sides of hydraulic cylinder, is the drain flow.

In any stage, be it telescopic or double acting,

- Raising
  - Flow Rate Q = Cylinder Bore Volume / Raising Cycle Time
- Lowering
  - Q = Cylinder Rod-Side Volume / Raising Cycle Time
- Obtain Volumes from Stroke, piston/rod diameters
- Drain Flow rate ~ = Forward flow rate / θ
  - Θ: Ratio of filling side volume to drain side volume

Drain Flow / Supply Flow = Other End Area / Supply End Area

For example, for a retraction, when supply end is rod side,

$Q_{drain} = Q_{supply}$ * (Bore-side area)/(Rod-side area)

SYMBOLS USED

V_b	Bore Side Volume
V_r	Rod Side Volume
Q_r	Rod Side Flow(through port)
Q_b	Bore Side Flow(through port)
V_{imp}	Implement speed(Raising speed)
P_{Or}	Rod Side Orifice Pressure Drop
P_{Ob}	Bore Side Orifice Pressure Drop
P_{raise}	Raising operation hoist valve setting
P_{lower}	Lower operation hoist valve setting
W	Load acting on cylinder

Requirement for Orifice Plate

Requirement:

To prevent overrunning load effect, the most commonly used component is counterbalance valve:

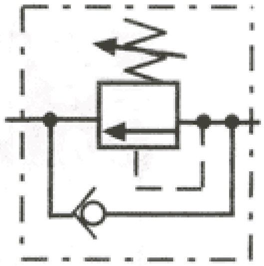


Image 19: Counterbalance valve (Resource: [12])

This valve prevents overrunning in a fixed load condition, but is ineffective in balancing cycle time.

Hence, a flow restriction valve is required. Of all the available options like solenoid valve, flow control valves, orifice plate is the best option due to the following reasons:

1. Cost factor: cheap
2. Ease of installation: Just requires a cut section of pipe, a flange can be installed with 4 bolts.
3. To change on-site cycle time either due to malfunction or for manipulation, just the orifice plate can be replaced with a plate of different bore hole diameter.
4. Maintenance: Hence, maintenance and serviceability is also good

Losses in an orifice plate

1. Throttling: System pressure is wasted in overcoming pressure loss across the restriction orifice plate.
2. Heat losses: Also due to recirculation, and other viscous effects, heat losses cause temperature rise of the oil.

Although by throttling, lot of energy is wasted, it is inevitable as it is the only way to control the flow output of a constant displacement input system.

Closed Center System

Closed center hydraulic systems rely on closed center circuits, or systems of interconnected components that move fluid, to provide pressure to the control valves, which partially or fully close or open, based on sensors that determine the level and rate of flow.

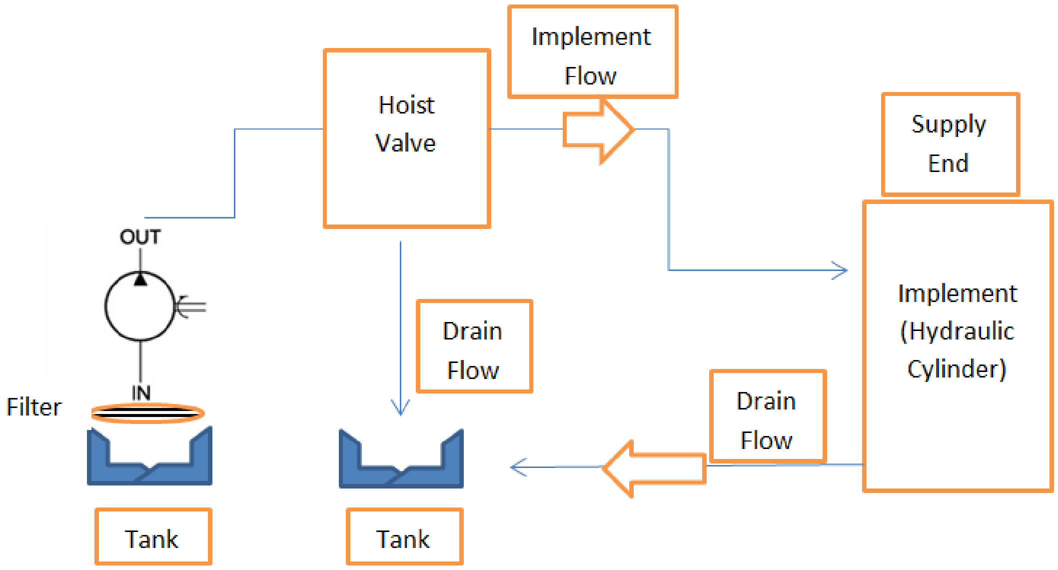


Image 20: Closed Center System

System:

1. Control valve(poppet valve) decides supply end of the implement
2. Can work at higher pressures than an open center system.
3. As oil is in a closed system, heating is problem, and required reservoir size is larger than in typical systems.
4. Case drain filter is fit in suction side of pump as fluid may collect debris on completing circuit.

Here, in the closed center system, the hydraulic cylinder also acts as a reservoir, and drain flow does not equal supply flow in a typical cylinder.

Overrunning load: a study

Overrunning load is encountered in a hydraulic cylinder, typically when the load is freely falling or accelerating in the required direction, but causes the actuator to fall faster than the pump can fill the oil. Oil leaves at high velocity at one end, but the supply end is starved of oil. Thus, a vacuum void is formed, which needs to be prevented at all costs.

Cavitation occurs in liquid systems and is the result of rapid formation and collapse of vapour bubbles in the liquid. Cavitation must be avoided or controlled as the collapse of vapour bubbles releases significant energy at the location of the bubble collapse. The consequences of this energy release are typically loud noise and pitting damage to contact surfaces, which over time may result in significant damage to or failure of equipment such as pumps or valves

Cavitation is often observed in control valves with very high pressure drops, where cavitation index falls to a very low value,

$$Cavitation\ Index\ C_i = {(P_{inlet} - P_{outlet})}\big/{(P_{inlet} - P_{vapor})}$$

where P_{vapor} is the vapor pressure of the oil.

For a square-edged concentric orifice plate, C_i>2 can avoid cavitation.

The cavitation index is a heuristic method for analysis of restriction orifice plates and valves, and the acceptable C_i will depend on the several factors including, flow stability, piping geometry near the orifice and the particulars of the orifice design.

In control valves, cavitation is usually tackled by multi-staging, but that is not possible in this case. Here, in overrunning load condition,

Theory:

1. During retraction stroke, lowering operation is performed. Here, supply end is rod side, and load force acts on the rod end in the same direction as supply oil pressure.
2. Hence, there is a chance that for given bore-side and rod-side orifice configuration, beyond certain load condition, pressure on rod-side can drop to very low values, leading to cavitation.
3. So, a upper limit on load is fixed, called over running load, beyond which control over the load operation is lost, which is not beneficial.

$$Pressure\ at\ supply\ end = 0$$

This causes irreparable damage to the cylinder.

Equations: Overrunning Load Calculation

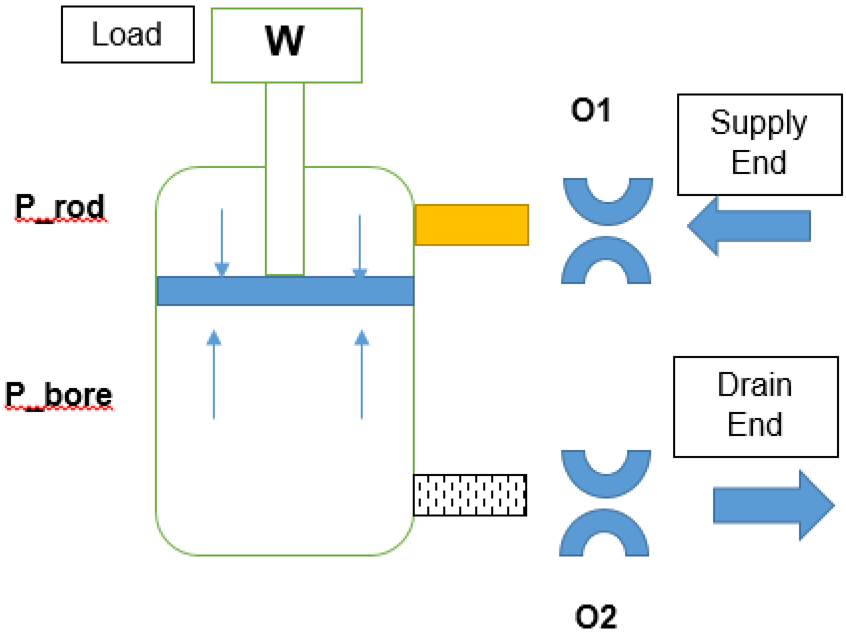


Image 21: Overrunning load analysis of cylinder

Let P_{O1} be pressure drop across orifice O1, and P_{O2} be pressure drop across O2.

$P_{supply} - P_{O1} = P_{rod}$(1)

$P_{O2} = P_{bore}$ (2)

Here P_{rod} *and* P_{bore} denote oil pressures on both sides of the actuator in the rod and bore side respectively.

Force balance:

$$\boldsymbol{W + \beta P_r * (A_r) = \beta P_{bore} * A_b}$$

Or,

$$\boldsymbol{P_r = P_{bore} * {}^{A_b}/_{A_r} - W/\beta A_r} \ .$$

To prevent cavitation, $P_r > 0$. Equality holds at overrunning condition.

Where A_r denotes rod-side area and $A_b$bore-side, and β denotes the cylinder friction factor mentioned in page <><>.

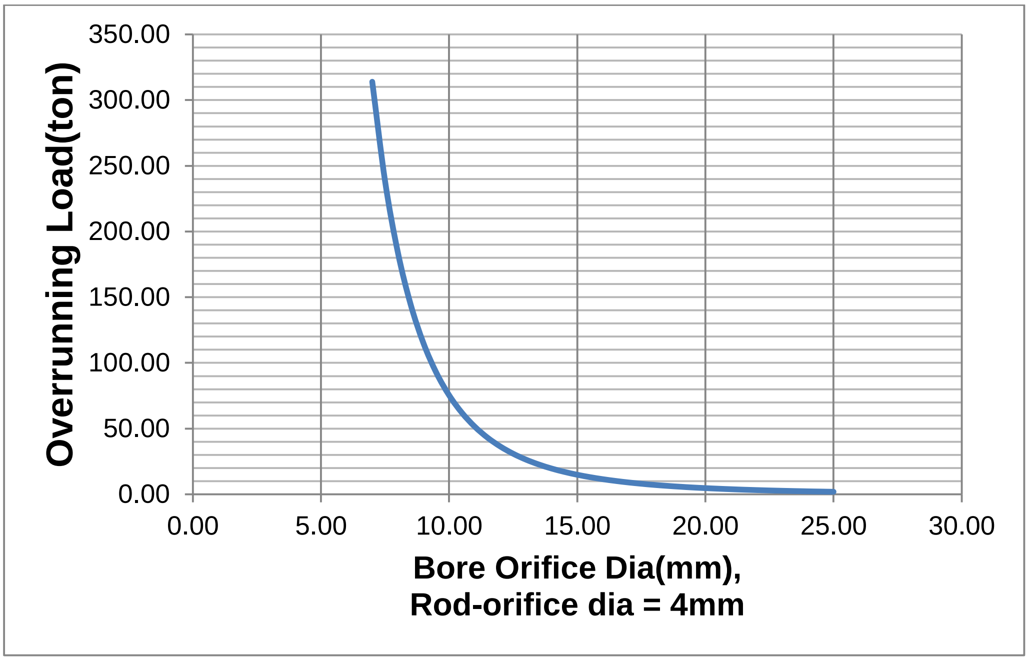
Performing calculations, we find that a relation between pressure drop in both orifice plates can be found. An upper limit on pressure drop in rod-side orifice as function of flow is thus found. Similarly a lower limit on bore-side orifice as function of drain flow is found.

Image 22: Cavitation effect(Source: forddoctorsdts.com)

Simplifying assumption:

$\boldsymbol{\Delta P}$ across orifice α Q^2 where Q is flow across orifice.

Although the real pressure drop is a complicated expression using ANSI standards, this assumption can used to find a range of ratio of diameters, and a critical diameter ratio. This will be an important design requirement of the system



Assumptions:

1. Minor pressure losses, line losses neglected, as they are hard to estimate, and require too much data.
2. Parabolic pressure drop – flow response assumed.

Orifice Plate Effect

There are two types of implement systems, pressure-controlled and flow-controlled.

1. Flow-controlled:

   Irrespective of the load on the system implement flow depends only the supply flow, usually from a variable displacement pump, or a constant displacement pump with variable speed.

2. Pressure-controlled:
   Here, for low loads, implement flow will be the supply flow, and after a cutoff pressure value set at relief valve, flow is reduced with increasing pressure.

The system in study is pressure controlled, from given details, hence cycle time balancing requirement is to be achieved.

That is, after cutoff,

$P_{system} = P_{relief}$, where relief valve setting is P_relief

$P_{system} = P_{load} + P_{restriction(orifice)}[Q] + P_{minor}$, Q: implement flow.

Expected $P_{restriction}[Q]$ response.

Hence the requirement is to provide required throttling $P_{restriction}$ so that for given supply pressure setting, the implement gets only that flow that gives it cycle time given by

$$Cycle\ Time = Supply\ End\ Volume\ /\ Implement\ \ Flow$$

Hence, from the input required cycle time, required implement flow is calculated, and required orifice can be sized.

Issue with model

1. Load pressure assumed to be constant throughout stroke, which is not true as the load is rotated through an angle.

Hence there is a requirement for cylinder tensile load study for various load angles.

Cylinder Load Study

The system in study is a generic implement where a double-acting hydraulic cylinder is connected to a slider crank mechanism, where the stroke of the cylinder is used to lift a load, usually from horizontal to a required maximum angle at maximum stroke. It can be extended to other systems like steering application where the cylinder force is used to overcome tire friction, for steering.

Mechanism used is a simple four bar mechanism. This is best suited, with a 3R-P mechanism, as minimizing linkage weights, and maximizing force transfer from cylinder to load is crucial to minimize required fluid pressure for given operation.

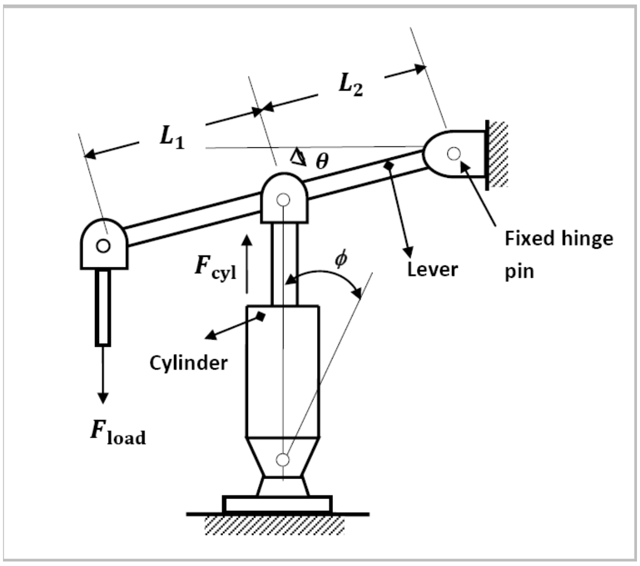


Image 23: Cylinder Force Balance (Source: NPTEL Fluid Power Control)

For example,

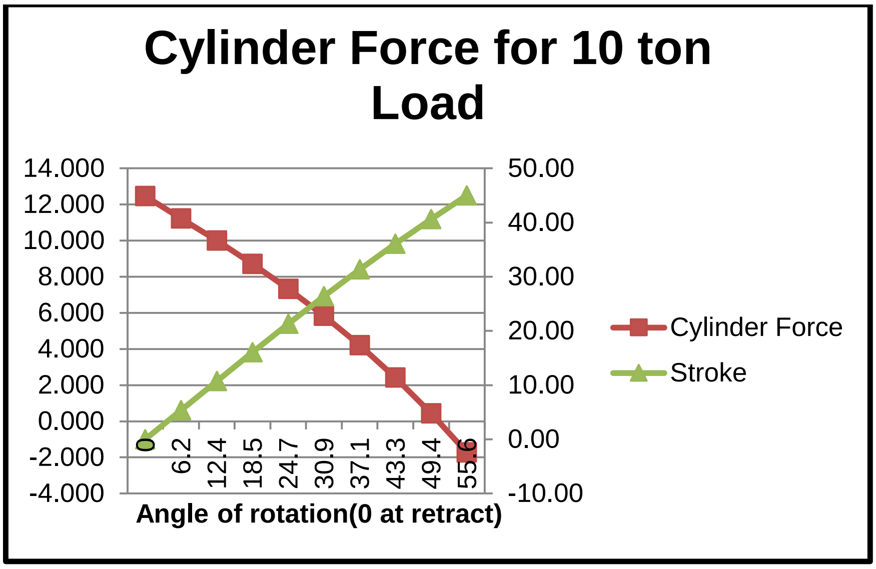
$$F_{cyl}\cos\phi \times (L_2\cos\theta) = F_{load} \times (L_1 + L_2)\cos\theta$$

Where ϕ, the cylinder drift angle is found from stroke input, or the required load angle of rotation about horizontal. Other factors like non-horizontal hinge connections etc. were considered, and a comprehensive mathematical model is developed to find effective tensile force on the cylinder, and lateral force on the pin at higher load angles.

Simple calculations taking moments about the main hinge is taken, and constant supply pressure on cylinder is taken. Assumed that the system moves at constant velocity, and hence moments are balanced.

Applications:

1. Finding maximum tensile force on cylinder normally, for a given retracted length of cylinder and stroke can be used to design cylinder rods and hence the entire cylinder sizing can be done



Three different applications are analyzed, and with these as templates, the model can be extended to a wide range of hydraulic implements.

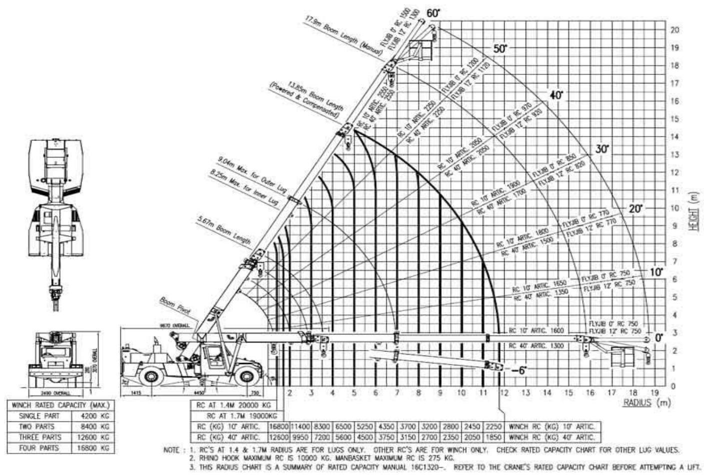
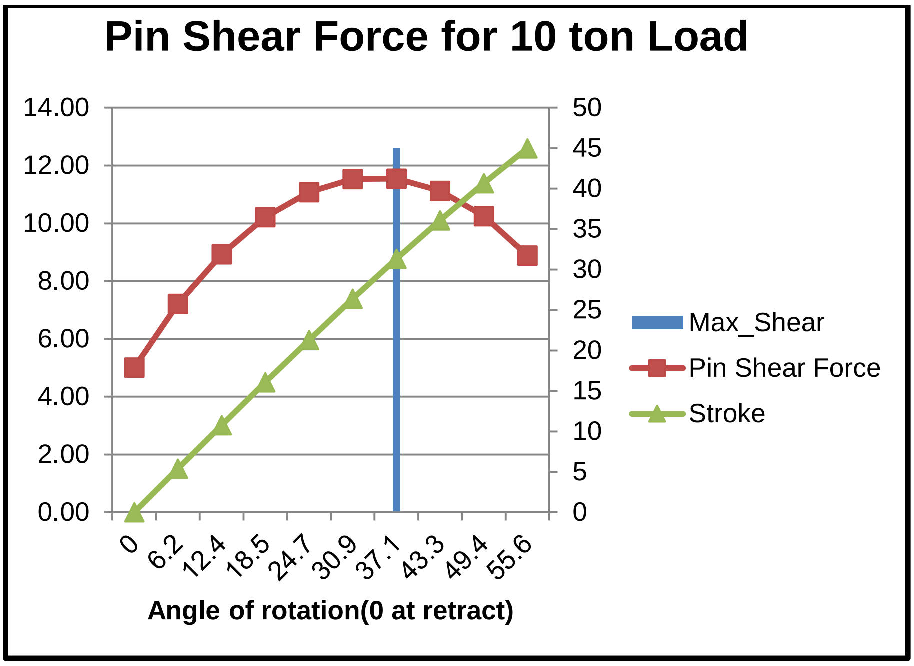


Image 23: Application example, calculating load capacity of slew crane w.r.t. arm length.

In slew crane, depicted above, it is important to know its load capacity for a given oil pressure, at different arm lengths, which can be calculated with this tool.

PIN FORCE CALCULATIONS

Maximum Pin force is used to design the pin, with structural failure criteria, and inputs taken are only the coordinates from the model, directly taken from a CAD model.



2. Lateral pin force is also found, and hence pin design for failure with appropriate factor of safety can also be performed.

Generalized Tool

Outputs and usage:

1. Provides data for designer on how placement of links, etc. affects maximum load that a slew crane can carry

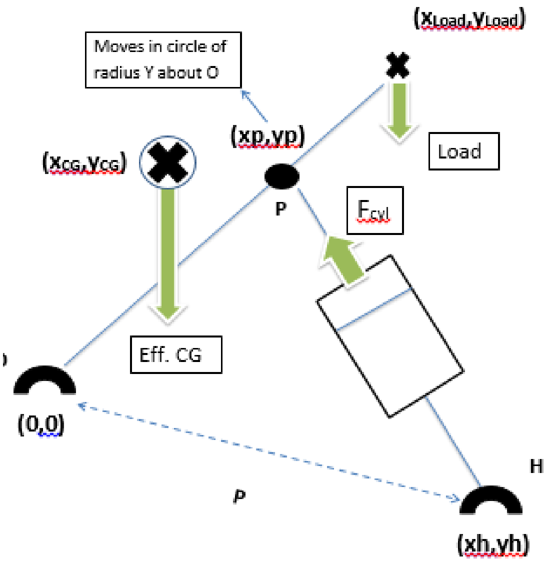
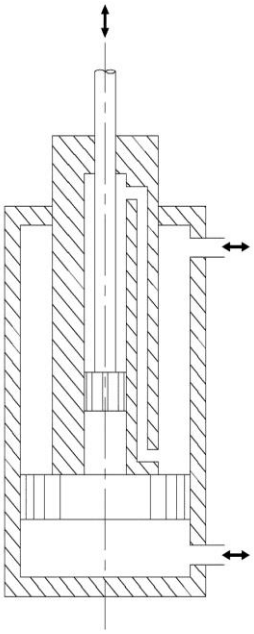


Image <>: Cylinder Load Study model

A mathematical model for effective tensile force on cylinder was developed.

Cycle Time Balancing



Balancing explanation:

- Rod Side Volume = roughly 1/3 * Bore Side Volume
- Used positive displacement pump(gear pump)
- So, raising operation: Time taken = Raising Cycle Time
- Lowering Cycle Time = Time to fill rod-side volume
- Hence, Lowering Cycle Time << Raising Cycle Time
- Thus required to fit orifice plates, to induce backpressure, so that flow is restricted so that cycle time is **balanced**

ASSUMPTIONS MADE

1. Load has no acceleration.
2. Line Losses not included
3. Staging effect:
   a. During either extending or retracting stroke, the supply end flow is assumed to be constant for both the stages(alternate assumption: extension speed is constant)
   b. Drain flow is assumed to be variable for both strokes, using each stage rod to piston area ratio.
4. Cycle Time effect:
   a. Supply end flow is taken to be ratio of supply side volume to cycle time.
   b. Assumed that implement flow is that which gives required cycle time, and rest is drained.
5. Valve effect:
   a. The operation is pressure-compensated, and depending on load pressure, orifice throttles flow to give required implement flow in hoist valve relief valve.

Losses

The overall efficiency of the system not only depends on the load and its duty cycle, but also on the nature of the power supply. As it can be understood from the Figure 2-4, most of the power is lost on the relief valve, due to the excess flow rate of the pump returning to the oil reservoir. Because the constant displacement pump is running at a constant speed there will be always an excess flow.

However, the requirement of the hydraulic circuit is to obtain a constant valve supply pressure independent of the load flow rate. Therefore, while supplying a constant pressure, the flow rate supplied by the pump can be adjusted through changing its displacement or its driving speed according to load flow rate requirement.

Heating effect: Remembering that the power loss in hydraulic circuits are absorbed by the hydraulic oil, an additional power is lost for the cooling necessities, which also increase the amount of the oil used, resulting in a bulky reservoir

Raise Cycle Time Matching

Steps:

1. For chosen orifice Dias D1, D2, find that Q_pump which gives force balance.$F_{load} + P_r * A_r = P_b * A_b$

2. $P_r = P_{O(rod)}$ $\quad \mathrm{P_b} = P_{raise(valve\ setting)} - P_{O(bore)}$

3. Using Q_{pump} , find achieved cycle time.

4. If not achieved, try diff. orifice configuration.

Lowering Cycle Time Matching

Steps:

1. For chosen orifice Dias D1, D2, find that Q_pump which gives force balance.$F_{load} + P_r * A_r = P_b * A_b$

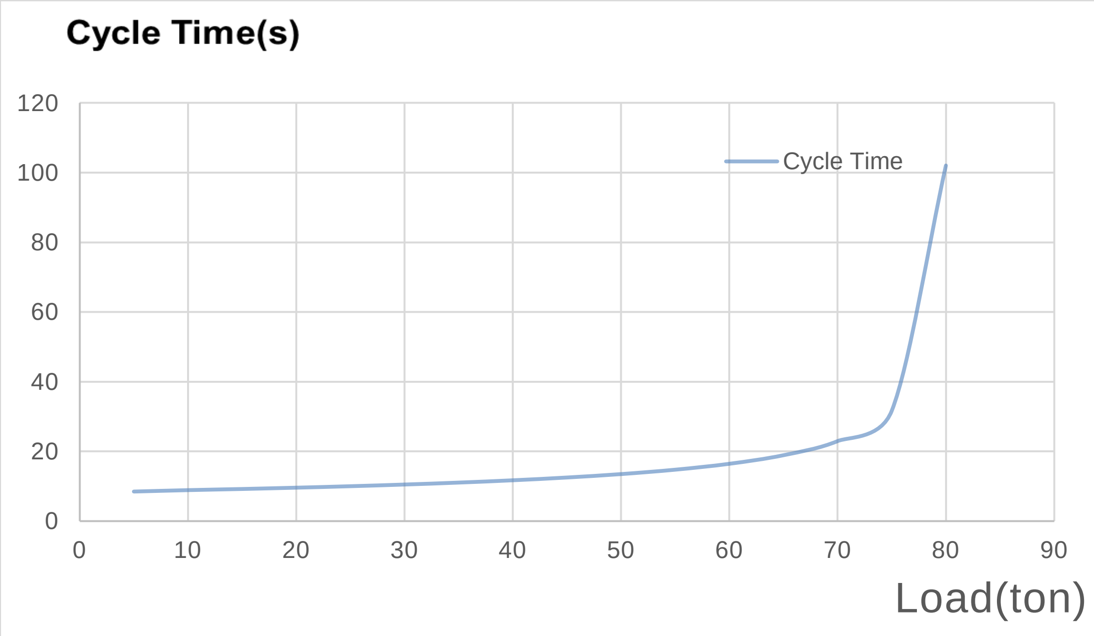
2. $P_b = P_{O(bore)}$ $\quad \mathrm{P_r} = P_{lower(valve\ setting)} - P_{O(rod)}$

3. Using Q_{pump}, find achieved cycle time.

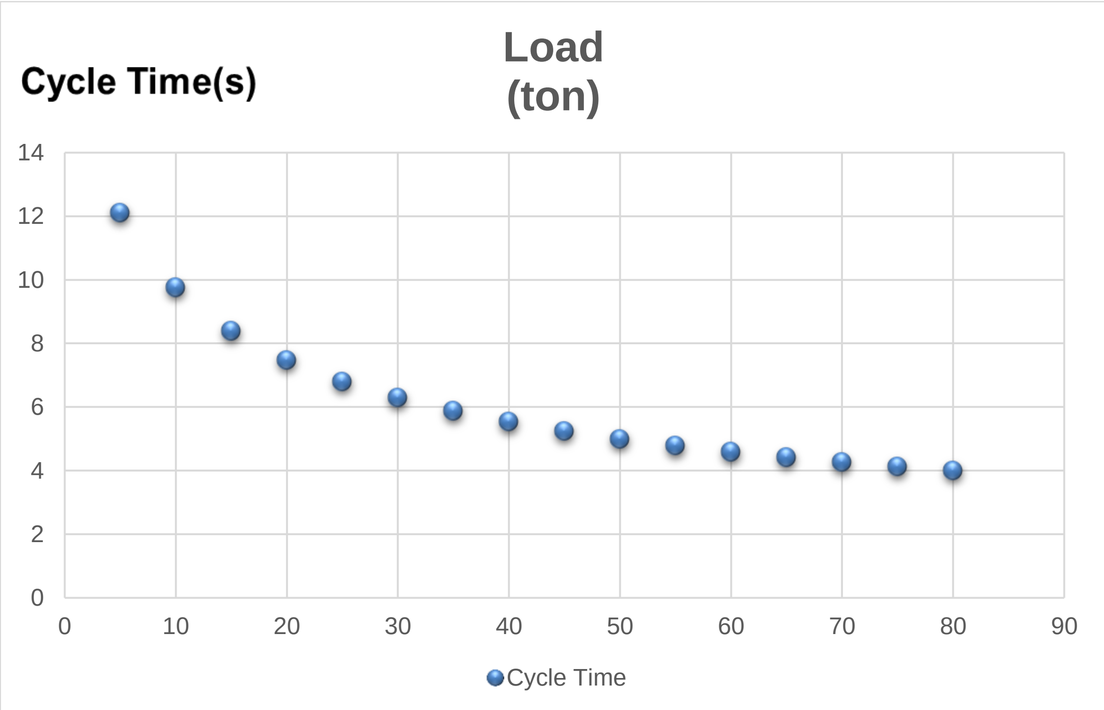
4. If not achieved, try diff. orifice configuration.

Cycle Time Load Impact

Raise Operation:



Lower Operation:



From above curves, shown from mathematical model, impact of load on cycle time, and the crucial requirement of appropriate load inputs.

Equations of Fluid Power Control

Raise Operation vs. Lower Operation:

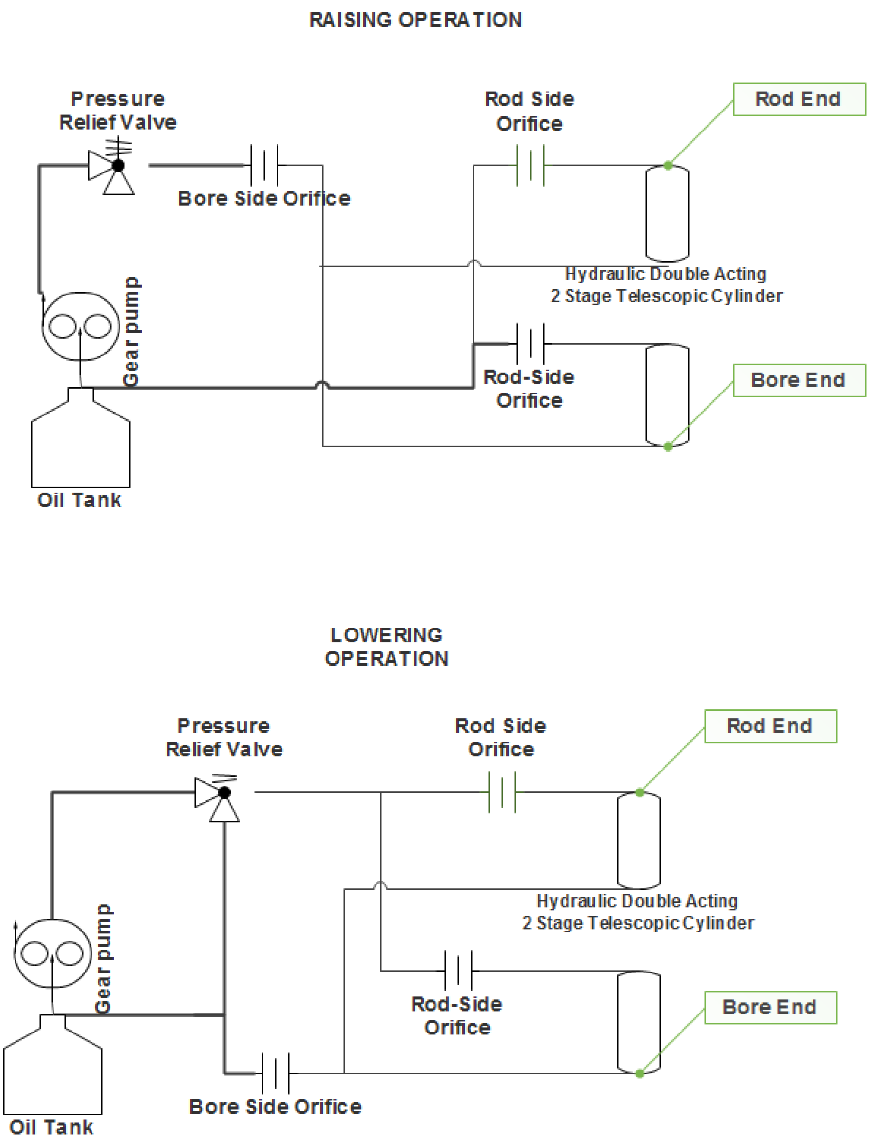
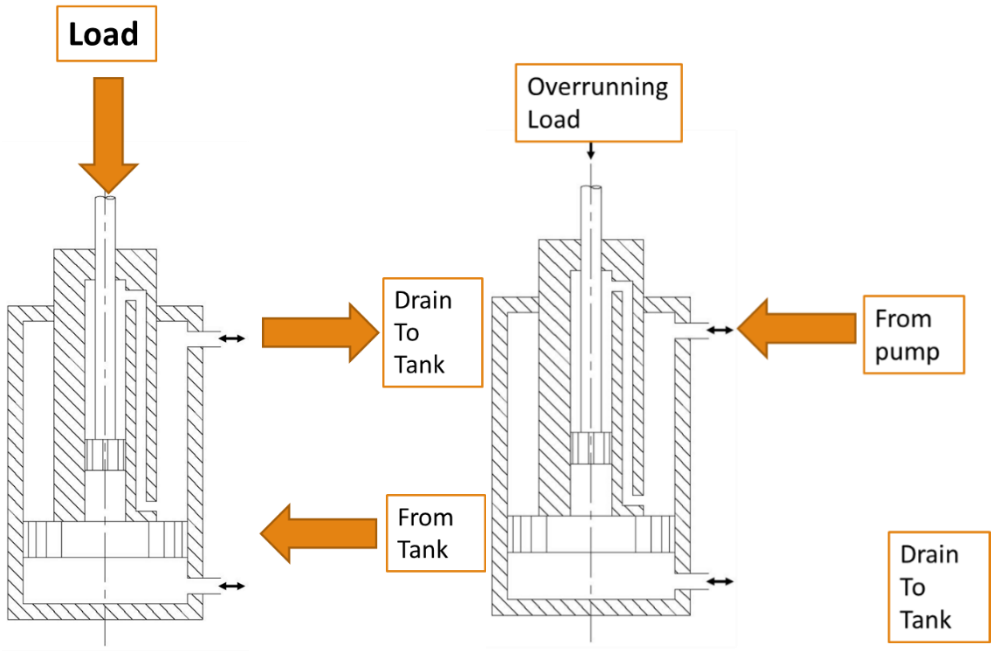


Image 24: Circuit connections for Lower and Raise operations

Clearly, we can see that for given cylinder volumes, and same cycle time required for raise and lower operation, drain flow and supply side flow in raise and lower operations respectively through both orifices is equal.

Hence, pressure drop in both operations is equal for the orifices. This gives only one free variables (implement flow), and two pressure balance equations. Hence pressure relief valve settings for both operations are crucial.

Sample Circuit Diagram



Raising Operation **Lowering Operation**

Image 25: Oil paths in each operation sketch

Balance Equations

Cylinder Pressure Relations	$F_{load} + P_r * A_r = P_b * A_b$	
Raising Operation	$P_r = P_{O(rod)}$	$P_b = P_{raise(valve\ setting)} - P_{O(bore)}$
Lowering Operation	$P_b = P_{O(bore)}$	$P_r = P_{lower(valve\ setting)} - P_{O(rod)}$
Over-running Load	$P_r = 0$	
Lowering Cycle Time	$Q_{rod} = \frac{(Rod: Side\ Volume)}{Lower\ Cycle\ Time}$	
Raising Cycle Time	$Q_{bore} = \frac{(Bore: Side\ Volume)}{Raise\ Cycle\ Time}$	

SYMBOLS USED

Q_{bore}: Bore-Side Flow (similarly Rod-side)

P_r : Pressure in rod-end of cylinder (similarly bore-side)

Sizing orifice from Required Pressure drop

- $Q/A = \boxed{C_d/\sqrt{1-\beta^4}\ \sqrt{2 * (\frac{\Delta P}{w}}) / \rho}$
- Highlighted terms: **Flow Coefficient**
  - Depends on d, D, Re only

w	• Head recovery ratio(ASME standards) • Depends on d, D
ΔP	Pressure loss across orifice
A	Hose Cross-Section $(\pi * \frac{ID^2}{4})$
β	• Ratio of orifice bore to hose ID • Depends on d, D
Cd	• Coefficient of discharge(ANSI standards) • Depends on Re, Hose ID D, Orifice dia d
Q/A	Flow velocity(known)

Orifice Plate Thickness

- When specifying a Restriction Orifice, the Plate thickness should be thick enough to reduce Plate deflection to a minimum.
- Expression for minimum thickness(mm) in Miller's handbook:
  - $Tmin = \sqrt{(0.681 - 0.651\beta) * \Delta P/Y}\ * D$, where D: Pipe ID
  - Where Y: Plate Material Yield Stress
  - **Sample Calculation**: For AISI 316 steel with 20 bar pressure, 25mm ID, 7.5mm orifice dia, min. thickness = 1.72mm
- ANSI standard: 0.05D is minimum thickness for minimum deflection condition for flowmeter application
- Uncertainty in C: Varies from 0.65%-0.78% with plate thickness [@@]

Energy formulation

Motor input power = Fluid Flow (fixed by RPM) * Operation relief setting / η

Where η is the conversion efficiency of gear pump.

Total Energy spent by pump = Input power * Operation time.

Final output is raising of load.

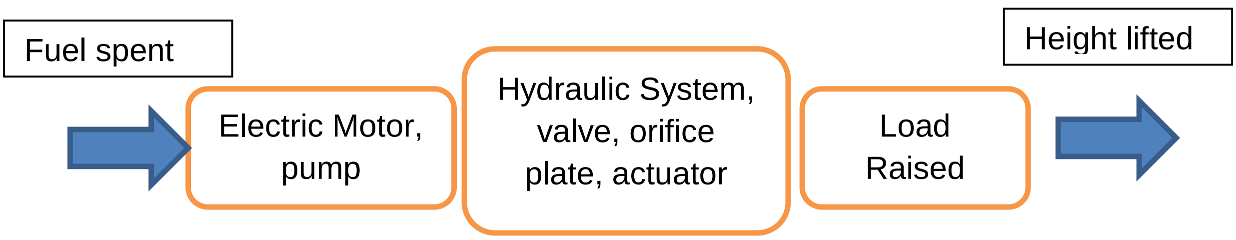
Hence, output mechanical energy = Load lifted * Height lifted

This can be calculated from geometric inputs.

Hence define overall system efficiency = Mech Output / Elec. Input

Uses:

1. Defined efficiency in terms of overall system integration, with all system integration
2. Hence, complete system improvement, cost analysis in terms of fuel burnt to complete the operation, an end-to-end analysis can be completed.
3. Variation analysis of dependence of parameters on efficiency can be used to optimize under-designed systems.
4. Some parameters which are generically decided like valve operation relief setting can be optimized, and the implement input flow, by manipulating RPM of motor.



Overall system analysis.

Orifice Sizing Algorithm

Cylinder,Pump,Valve Details, Hose Dia INPUT

- Hoist Valve Relief Setting for Raise, Lower Operations INPUT
- Pump flow INPUT

↓

Cycle time INPUT

- Calculate Flow Details
- Calculate Reynolds number,C_d

↓

INPUT Load (=Empty Body Weight)

- Calculate eff. tensile force on cylinder
- Assume: $F_{load} + P_r * A_r = P_b * A_b$

↓

Orifice Plate Sizing: Over running Condition(Lowering Operation)

- Calculate Overrunning load as function of
- Orifice Diameter(s), and constraint: Load < Overrunning Load

↓

For required Cycle Time-> Implement Flow

- Required Pressure Drop in both Orifices Calculated
- Line Losses NOT considered

↓

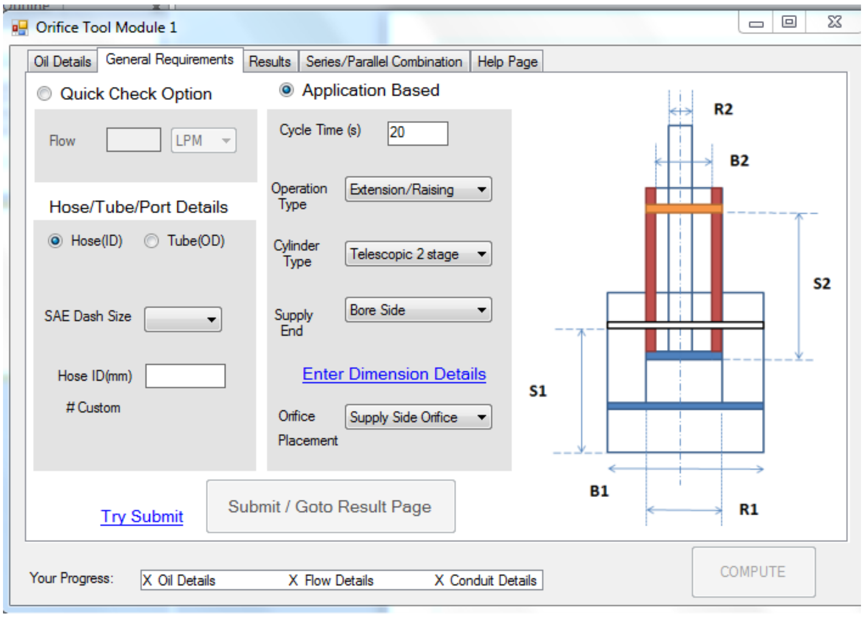
From Pressure Drop Required, Flow, & Over-running Condn.=> Orifices Sized

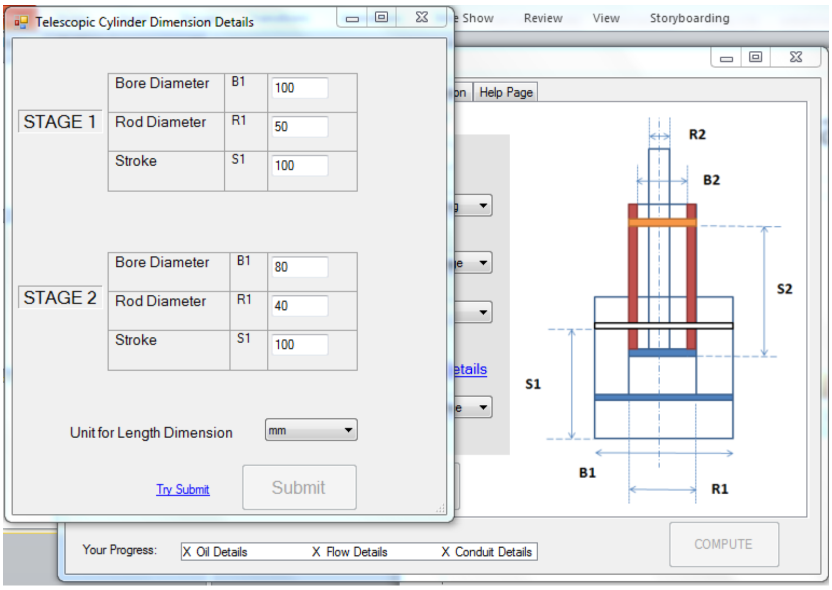
- Hence both Orifice Diameters found.

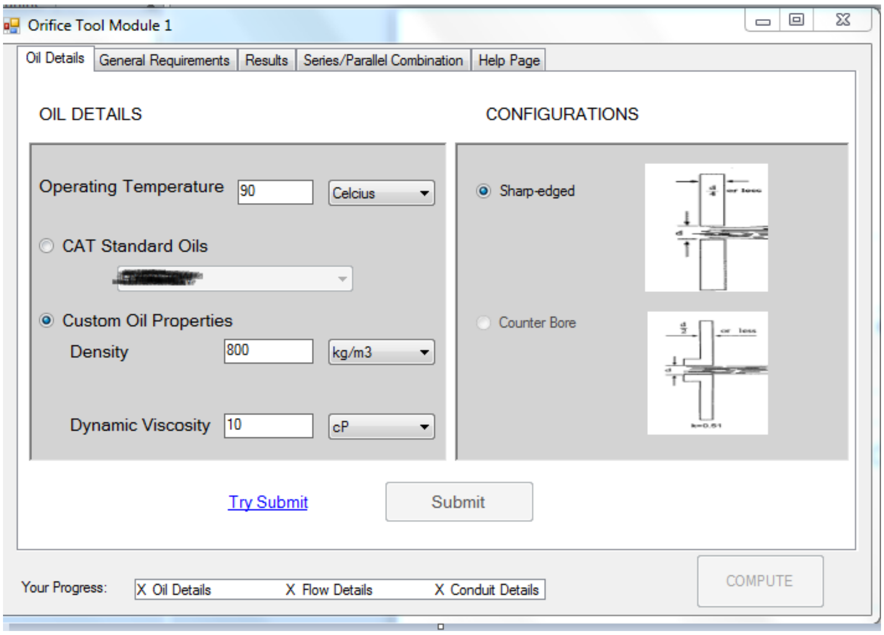
Software Tool for Orifice Sizing

Requirements: Input Cylinder dimension Details and operation details

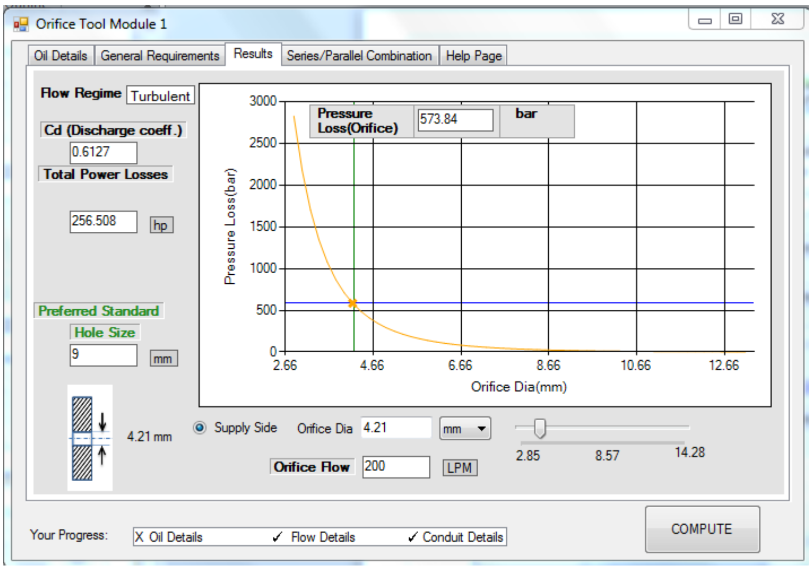
1. Enter Cycle time details
2. Enter Hose Details
    a. Use SAE dash sizing
3. Cylinder type to be chosen, and operation supply end.
4. Choice of orifice position – in supply end or drain end is chosen







5. Input Oil Details from a database
    a. Dropdown with auto fill from CAT database used.
    b. Custom option to directly enter properties present
6. Configuration of orifice, user input



Interactive user interface for pressure drop calculation, with slider to vary orifice diameter made.

Improvements over simple Orifice Sizing Tool

- Capabilities of simple tool:
  - Given any 3 of flow rate, pressure drop, orifice area, Cd (discharge coefficient), the other is found.
  - Finds effective orifice area for series and parallel configurations
  - Chart for choosing Cd based on choice of orifice shape
- Additional capabilities of built tool:
  - Perform sizing of orifice based on cycle time requirement
  - Compares different orifice configurations, chooses best for cost reduction
  - Considers Reynolds number effect on discharge coefficient C_d
  - Computes orifice energy losses
  - Considers full system integration
  - Curves of different flow characteristics output
  - Cycle time effect with orifice diameter curve
  - Considers standard orifice sizes available, and considers thickness dimension also
  - Can be expanded for different configurations, power law relations between discharge coefficient and Re used.

Conclusion

1. Orifice Plate Pressure Loss calculator with implement specific inputs made conforming to ANSI standards, and other standards studied and documented.
2. Literature Study on various orifice plate configurations and power law relations for discharge coefficient found.
3. Orifice Sizing Tool with complete system integration for hoist application, and a general tool for orifice pressure drop calculation developed.
4. Maximum customization in all inputs provided, in cylinder type, orifice position etc.
5. Software tool with graphical user interface, for sizing orifice plate from required pressure drop in a given hydraulic circuit with minimal inputs generated.
6. Cylinder Force Calculator with only coordinate points input details to calculate variation of pin force and cylinder force from load, can be used for
   6.1. Cylinder Sizing from maximum tensile load, and buckling considerations
   6.2. Pin design, from maximum lateral stress, and factor of safety.
   6.3. Cylinder dynamics with stroke, cycle time impact
7. Mathematical model for entire system integration, estimating significant losses in orifices and valve estimated.

Further Improvements

1. Integrate with line losses tool, and include various other configurations for cost-effective minimum loss effect.
2. Extension to other implements with similar configurations
3. Cycle time impact due to varying load with angle of implement with horizontal to be studied
4. Add buckling module and cylinder sizing from load requirement for hoist implement design.

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