Hydraulic Conveying of Bulk Materials

AGENDA

1. Overview  
   - historical  
   - applications  
   - material characteristics  
   - system characteristics

2. Pump Types  
   - Centrifugal  
   - Positive Displacement  
   - Other

3. Pipelines
4. Slurry Basics
5. Newtonian Fluids
6. Non-Newtonian Fluids
7. Friction Losses
8. Settling Velocities
9. Centrifugal Pump Systems
10 Head ratio and Efficiency ratio
11 Slurry System Analysis
Use of hydraulic conveying over short distances for alluvial mineral separation was documented in the 16th century.

Ref: De Re Agricola - Georgius Agricola, 1556
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OVERVIEW - Historical

- Slurry transport by gravity flow in flumes and pipes has been common for over 100 years
- Short distance hydraulic conveying using slurry pumps developed during the 20th century, mostly in the mining industry.
- In the 1950’s **long distance** pipeline slurry transport was introduced.

<table>
<thead>
<tr>
<th>Material Pipeline</th>
<th>Length (km)</th>
<th>Pipe Dia. (m)</th>
<th>Capacity (Mtpa)</th>
<th>Start-up Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consolidation Coal USA</td>
<td>Coal</td>
<td>174</td>
<td>0.25</td>
<td>1.3</td>
</tr>
<tr>
<td>Savage River Tasmania</td>
<td>Iron Ore</td>
<td>85</td>
<td>0.23</td>
<td>2.25</td>
</tr>
<tr>
<td>Black Mesa - USA</td>
<td>Coal</td>
<td>439</td>
<td>0.46</td>
<td>4.8</td>
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<tr>
<td>Freeport - Indonesia</td>
<td>Copper Concentrate</td>
<td>111</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td>Samarco - Brasil</td>
<td>Iron Ore</td>
<td>407</td>
<td>0.5</td>
<td>12</td>
</tr>
</tbody>
</table>

Ref: Solid-Liquid Flow, Slurry Pipeline Transportation – Wasp, Kenny, Gandhi. 1977

- Long Distance pipelines are now commonplace in the mining industry for conveying concentrate.
OVERVIEW - Applications

A FEW EXAMPLES OF HYDRAULIC CONVEYING WITH CENTRIFUGAL PUMPS

• Offshore shiploading of iron sand - New Zealand
• Dredging and land reclamation
• Pumping sugar beets
• Co-Disposal of fine tailings slurry and coarse rejects
  Replacing trucking of coarse Rejects + pumping of fine tailings
OVERVIEW - Applications

A FEW EXAMPLES OF HYDRAULIC CONVEYING WITH CENTRIFUGAL PUMPS

• Plant feed of oil sand ore - lumps up to 100mm - Canada

Two sets of two stages of Warman 550 U-SHDU pumps handling oil sand with lumps up to 100mm. 5700 m³/hr of slurry at 55m head per stage. Slurry SG=1.65. 1800 kW motors

Warman 20/18 TU-AHP high pressure pumps in series handling oil sand slurry
OVERVIEW - Material Characteristics

- **MATERIAL SIZE**
  - Maximum particle size which can pass through pump
    - Positive Displacement Pumps - max 15mm.
    - Centrifugal Pumps - dependent on pump size, up to 100mm not uncommon.
  - Influence of particle size on slurry characteristics
    - Very fine particles result in viscous slurries but allow low transport velocities and low pipeline abrasion.
    - Coarse particles result in settling slurries, high transport velocities, greater wear on pumps and pipes.
    - Particle size degradation can occur during transport.
  - Hardness and particle shape
    - Wear on pumps and pipes increases with harder and sharper particles
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OVERVIEW - System Characteristics

• **WET vs Dry**
  - If the material processing before or after transport is wet then hydraulic transport should be evaluated:
    - Will the particle size have to be reduced to facilitate hydraulic transport? At what cost?
    - Should the slurry be densified to reduce system costs?

• If the material processing is dry then the consider the following:
  - Is sufficient water available to create a slurry?
  - Does the water have to be returned to its source and clarified?
  - What is the cost of dewatering the material after transport?
  - Will the particle size have to be reduced to facilitate hydraulic transport? Cost?
PUMP TYPES

• CENTRIFUGAL SLURRY PUMPS
  • Handle high flow rates, shorter distances (typically up to 10 km)
    large particles (typically up to 100 mm)
    and have lower capital cost.
**CENTRIFUGAL SLURRY PUMPS**

- Multiple stages required for high pressures due to relatively low head developed.

- Wide range of wear resistant materials of construction available - elastomers, metals.

- Typically used in mineral processing plants and for tailings disposal and sometimes plant feed.
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PUMP TYPES - Centrifugal

Increasing Efficiency

Specific Speed Ns

Increasing Capital cost

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PUMP TYPES

MATERIAL

Gravel, Shingle, Scree

Coarse sand

Medium sand

Fine sand

Silt

MEDIAN SOLID PARTICLE SIZE: $d_{50}$ [mm]

PUMP TYPES

DREDGE AND GRAVEL PUMPS

SLURRY PUMPS

Elastomer, impellers and liners

Metal impellers and liners or casings

Piston Diaphragm Pumps
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PUMP TYPES

**POSITIVE DISPLACEMENT PUMPS** (PDP’s)

- High efficiency
  - up to 93% for large piston diaphragm pumps
- Low wear due to low internal velocities
  - except for valves which require replacement typically every 2000-5000 hours with abrasive slurries
- Higher pressures than centrifugal pumps
  - up to 250 bar (25 Mpa) vs approx 7 Mpa for centrifugals
- Handle higher density, higher viscosity slurries than centrifugal pumps
- Generally used for high pressure, lower flowrate applications and have high capital cost.
Duplex Double-acting Piston Pumps
•Large number of wearing parts in contact with slurry.
•are in common use in the oil well drilling industry, are operated at speeds of up to 125 strokes per minute

Triplex Single-acting Piston Pumps
Due to single-acting design the piston rods are not in contact with the slurry and the need for stuffing box packing has been eliminated.
• Used in oil industry up to 160 strokes /min.
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PUMP TYPES - PDP’s

**Triplex Single-Acting Plunger Pumps**
- To protect the plungers against the abrasive action of the slurry a plunger water flushing system is provided which dilutes the slurry.
- Have high wear rates on abrasive slurries. Operate 100-140 strokes/min.

**Piston Diaphragm Pumps**
- Developed by GEHO in duplex double acting and triplex single acting, all the pump parts are protected from the slurry by a rubber diaphragm. The valves are the only wear parts.
- Run at 40-80 strokes/min. with large valves having flow velocities 0.8-1.5m/s through the valves and consequent long valve lives.
Key features of the GEHO piston diaphragm pump

- Pulsation dampener
- Discharge valve
- Pressure relief valve
- Diaphragm housing
- Pump diaphragm
- Piston
- Suction valve

Liquid end
Power end

Wearing parts
Slurry
Nitrogen
Oil
Propelling fluid

USA: transport of phosphates slurry - JR Simplot.
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PUMP TYPES - Others

• OTHER PDP’s
  • Peristaltic Pumps
    • Low capacity
  • Progressive Cavity helical rotor
    • Small particle size

• Jet Pumps
  • Low cost, low head, low efficiency eductor

• Air Lift
  • Low efficiency
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PIPEDINES

- **Materials**
  - Unlined steel pipe used for fine slurries
  - High Density Polyethylene (HDPE) has good erosion and corrosion resistance for fine slurries but low pressure rating.
  - Rubber lined and polyurethane lined steel pipe common in mining industry with coarser particles.

- **Wear**
  - Higher wear at bottom of pipe with settling slurries
    - Pipe can be rotated to increase life.

- **Maintenance**
  - Flushing, draining, access for unplugging.

- **Route**
  - Terrain - If pipe has negative gradient in excess of friction gradient slack flow will occur causing high wear rates. Choke stations may be required.
  - Pump station locations. Check hydraulic gradients. Pipe pressure ratings.
Slurry is a composition of solids and a carrying liquid. The specific gravity of the slurry is also its weight per unit of volume compared to water. Slurry specific gravity will go typically from 1.01 to 2.5. Occasionally, it may be below 1.0 if in a chemical carrier.

In general, a water-solids mixture may not be pumpable above around 60% Cv with a centrifugal pump. Generally 50% Cv is the practical upper limit. This is highly dependant on particle size sieve analysis.
The specific gravity of a substance is equal to the ratio of the weight vs the weight of an equal volume of water. This is a comparison of a submerged density not bulk density.

(SG of 20% Cv Slurry)

- Coal is about 1.35 - 1.5 times water. (1.1)
- Lime is 2.4 times the weight of water. (1.28)
- Sand is 2.65 times the weight of water. (1.33)
- Copper ore is about 4.6 times water. (1.72)
- Iron ore concentrate is about 5.2 time water. (1.84)
- Lead ore is about 7.6 times water. (2.32)
- Metallic nickel is about 8.9 times water. (2.58)
### Specific gravity and Concentration equations for Slurries

<table>
<thead>
<tr>
<th></th>
<th>Sw</th>
<th>=  S(SmCw–Sm) / (SmCw–S)</th>
<th>=  (Scv–Sm) / (Cv–1)</th>
<th>=  S[Cv(Cw–1)] / [Cw(Cv–1)]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SG of Liquid</strong></td>
<td>S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SG of Dry Solids</strong></td>
<td>S</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SG of Slurry</strong></td>
<td>Sm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Concentration Of</strong></td>
<td>Cw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Solids by Weight</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Concentration of</strong></td>
<td>Cv</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Solids by Volume</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Cv and Cw are expressed as decimals not percentages in these equations

Another useful relationship is:  \( Cw/Cv = S/Sm \)
Preliminary estimate of characteristics of a slurry:
• Settling
• Non-Settling
Newtonian Fluids, Viscosity

- When a shear force is applied at a boundary of a fluid, the latter begins to move in the direction of the force, developing shear stress between adjoining layers. This property of the liquid is called **Viscosity**

- If the velocity gradient (shear rate) $dv/dy$ between any adjacent fluid layers is constant the fluid is Newtonian

**Shear Stress at wall** $\tau_w = \frac{PD}{4L}$

$P$=pressure differential
$L$=pipe length

Dynamic viscosity $\mu$
Reynolds Number

• A dimensionless “Reynolds Number” \( N_R \) for flow in pipes, is defined as:

\[
N_R = \frac{\rho DV}{\mu}
\]

• Laminar flow exists at Reynolds numbers up to 2000. At values between 2000 and 3000, flow is transitional with both forms of flow existing in the pipeline.

• Liquids are pumped in turbulent flow at low velocities from 0.5 to 2 m/s because they yield the best compromise between pipe friction losses (running costs) and capital costs (pumps and pipework cost).

• Slurries of liquids and settling solids are pumped in turbulent flow at higher, safe velocities from 2 to 5 m/s or more, in order to prevent pipe blockages.

• Slurries of liquids and fine, non-settling solids usually form homogeneous slurries and are pumped at intermediate velocities between 1 and 3 m/s at Reynolds numbers close to 2000.
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Non-Newtonian Fluids - Bingham Fluids

• When high percentages of fine-sized solid particles (of less than 0.1 mm) are mixed with water, they usually form slurries, which do not behave like Newtonian fluids and in which the solids usually do not settle.

• If an applied shear stress is above $\tau_0$, the material begins to flow.

• We need to calculate $V_c$, the critical average velocity at the end of the laminar flow range. This usually occurs at a Reynolds number of 2000.
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Non-Newtonian Fluids - Bingham Fluids

• Critical Velocity \( V_c = X_1 + \sqrt{(X_1^2 + X_2)} \) where:
  
  \[
  X_1 = \frac{\eta N_R}{(2 \rho_m D)} \quad \text{and} \quad X_2 = \frac{\tau_0 N_R}{(8 \rho_m)}
  \]

• At velocities lower than \( V_c \), flow is laminar and total head \( H_m \) varies relatively little with changes of flow rate \( Q \).
• Pumping costs are therefore approximately directly proportional to flow rate. At velocities higher than \( V_c \), flow is turbulent and head and pumping costs vary parabolically.

• The most economical pumping velocity is therefore the one nearest to \( V_c \).
There are three common cases of friction in pipes:

- **Liquids**
  - Use the Darcy or Hazen & Williams methods

- **Homogeneous, non-settling slurries**
  - Use Bingham slurry method after carrying out rheological tests on slurry samples with a viscometer

- **Heterogeneous slurries containing settling solids**
  - For long distance pumping applications pipeline testwork should be done on the slurry
  - For short pipelines water based calculations are usually sufficient
EXAMPLES:
Pumping at \( V=3 \text{ m/s} \) through steel pipe \( D=0.25 \text{ m} \) with wall roughness \( e=4\times10^{-6} \text{ m} \).
1. Water at \( T=20^\circ \text{C} \):
   - Kinematic viscosity: \( \nu=10^{-6} \text{ m}^2/\text{s} = (1 \text{ cSt}) \).
   - Start with \( D \) from bottom left and bottom right and follow the arrows to the end to get \( f=0.0145 \) and:
     \[ H_f=3.0 \text{ m water} / 100 \text{ m pipe}. \]
2. Linseed oil at \( T=70^\circ \text{C} \):
   - Kinematic viscosity: \( \nu=10^{-5} \text{ m}^2/\text{s} = (10 \text{ cSt}) \).
   - Start as above but stop at \( D \), read \( N_r=7.8\times10^5 \), divide it by 10 (cSt) to get new \( N_r=7.8\times10^4 \), enter it at \( C \) and continue to the end to get \( f=0.0197 \) and:
     \[ H_f=3.7 \text{ m linseed oil} / 100 \text{ m pipe}. \]
   - (Note: cSt=centistokes)
HAZEN-WILLIAMS PIPE FRICTION DIAGRAM
for Water at 20°C

EXAMPLE:
Flow in various pipe materials:
D=0.15 m  V=1.2 m/s

<table>
<thead>
<tr>
<th>Pipe material</th>
<th>C</th>
<th>Hf</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rubber</td>
<td>110–130</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basalt</td>
<td>120–140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steel</td>
<td>130–150</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastics</td>
<td>140–160</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pipe roughness: C
Friction Head: Hf|100 [m water / 100 m pipe]
PIEVELOCITY: V [m/s]
PIPE FLOWRATE: Q [L/s]
PIPE DIAMETER: D [m]
• When the sizing, density and concentration of solids in a slurry are known, we can determine the average Limiting settling velocity \( V_L \) of the slurry, which will move the solids and not let them settle.

• Two commonly used methods to estimate settling velocity are the Durand and Wilson methods. These are sufficiently accurate for designing in-plant short distance pumping systems.

• For long distance pumping systems, pipeline test work should be done to accurately estimate settling velocity.
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Settling Velocities - Heterogeneous Slurries

DURAND’S LIMITING SETTLING VELOCITY DIAGRAM

- PIPE DIAMETER: D [m]
- CONCENTRATION BY TRUE VOLUME: Cv [%]

- SOLIDS SPECIFIC GRAVITY: S [-]
- PARTICLE DIAMETER: \(d_{50} [\text{mm}]\)
- LIMITING SETTLING VELOCITY: \(V_L [\text{m/s}]\)

DURAND METHOD

- is conservative (high velocity estimate)
- based on narrowly graded solids

EXAMPLE:

\(d_{50} = 0.5 \text{ mm}\)
\(Cv = 5\%\)
\(D = 0.2 \text{ m}\)
\(S = 2.65\)

\(V_L = 3.4 \text{ m/s}\)

\(F_L = 1.34\)
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Settling Velocities - Heterogeneous Slurries

Wilson’s Deposition Velocities

Wilson Method

- lower velocity estimates than Durand
- applicable to highest pumpable solids concentrations.

Example:
Solids of specific gravity $S=2.65$ and particle size $d_{50}=0.19$ mm are to be pumped through a pipe of diameter $D=0.150$ m.
The highest expected deposition velocity is:
$V_c = 1.95 \pm 0.40$ m/s.
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Friction Losses in Pipes - Heterogeneous Slurries

GRAPHICAL METHOD FOR APPROXIMATION OF SLURRY FRICTION

- $Q_L$ corresponds to settling velocity in pipeline
- Slurry $H_F$ is lowest at $0.7Q_L$
- $Q$ is the duty flowrate
- $1.3Q_L$ is where water and slurry have same $H_F$
Energy, Head, Pressure

• ENERGY
  • Specific energy of a fluid is equal to its elevation or potential Head, $Z$

• VELOCITY HEAD
  • A form of energy
    $H_v = \frac{V^2}{2g}$

• PRESSURE
  • A function of the height and density of a fluid
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Centrifugal Pump Systems

Pump Performance Curve

Duty Point

Pipe System Resistance Curve
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Centrifugal Pump Systems

Fixed speed operation

H
rpm

ho
hd
hf
Low sump level
Med sump level
High sump level

Q1  Q2  Q3
Q
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Centrifugal Pump Systems

Variable speed operation

DO NOT CONTROL SUMP LEVEL WITH A Variable Speed Drive
1. Settled line
2. Suction liner collapse
3. Poor wear
Control Valves

**Figure 2-9** Typical graph showing system variations
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Centrifugal Pump Systems

Multi-stage Pumps

Figure A7-3 Four-stage pump unit
WEIR WARMAN LTD.

Typical Centrifugal Slurry Pump Performance Curve

**Best Efficiency Point (BEP)**
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Head Ratio & Efficiency Ratio

- The flow of solids through a centrifugal pump causes its performance on slurry to differ from that on water due to:
  - Slip between the water and solid particles
  - Energy losses as the solids can only absorb kinetic energy and cannot transform it into pressure.
  - Increased friction losses

\[
\text{Head Ratio} = \frac{H_m}{H_w}
\]

Head Ratio = Hm/Hw

All tests at 510 r/min


HR = 0.85
ER = 0.82
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Head Ratio & Efficiency Ratio

HEAD RATIOS AND EFFICIENCY RATIOS FOR PUMPING SOLIDS

SOLIDS MEDIAN PARTICLE SIZE: $d_{50}$ [mm]

Empirical estimate.

Based on testwork.

Sufficiently accurate for most systems.
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Slurry System Analysis

- Determine flow rate
- Determine static head
- Determine pipe diameter
  - Limiting settling velocity (heterogeneous)
  - Critical velocity (Non-Newtonian)
- Calculate friction head
- Calculate Total Dynamic Head (system curve)
- Select pump type, size and materials
  - Number of stages, pressure rating
- Determine Head & Efficiency ratios
- Plot pump & system curves
- Check NPSH
- Calculate required power
• TOC for a slurry pump consists of:
  – capital (depreciation, cost of capital)
  – energy (absorbed power, drive losses)
  – maintenance (parts, labour, down-time)
  – inventory (capital tied up)
  – gland water (both supply and removal)
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Total Ownership Cost - TOC

- Energy
- Materials
- Capital

Part wear life (hrs) vs. % of TOC
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presented by
Geoff Moore

General Manager
Pump Technology Group
Weir Minerals Division