Energy efficient thermal retrofit options for crude oil transport in pipelines

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Most economic method for oil & gas transportation over land.

Gradual depletion of conventional oil reservoir is leading to:
- Remote locations
- Unconventional oil (Heavy oil, tar sands…)

Consequence:
- Increased transport costs and technical difficulties
Pipeline design – Pressure Drop

• Pressure drop ($\Delta P$) mainly depends on:
  – Friction
    • Viscosity: $\uparrow \mu \rightarrow \uparrow \Delta P$
    • Throughput: $\uparrow$ Flowrate $\rightarrow \uparrow \Delta P$
  – Ground elevation

• Thermal effects:
  – Viscosity increases exponentially with $\downarrow T$
  – Gradual cooling along pipelines:
    • $\uparrow \Delta P$ (& pumping cost)
    • $\downarrow$ Flowrate; eventually flow inhibition

› Shift to heavier oils ($\uparrow \mu$)
  › Pipeline design/Drag Reduction Techniques

› How likely is a shift to more viscous oils?
Unconventional Oil Resources

- ~ 50% of recoverable oil resources is unconventional (heavy oil, tar sands and bitumen) (IEA).
- ~ 87% of unconventional oil in Canada, Venezuela and Russia.
- Russia has focused on production of conventional oil (1st World producer in 2011 (IEA)), but unconventional oil largely unexploited.

Russia Oil Pipeline Network

Huge pipeline network mainly developed for conventional oil.

Ref. news.bbc.co.uk (2006)
### China-Russia Pipeline

<table>
<thead>
<tr>
<th><strong>CRCOP</strong></th>
<th><strong>ESPO</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operation Mass flowrate Mtons/yr</td>
<td>15</td>
</tr>
<tr>
<td>Pressure (MPa)</td>
<td>8 to 10</td>
</tr>
<tr>
<td>Inner diameter (m)</td>
<td>0.7812</td>
</tr>
<tr>
<td>Depth buried (m)</td>
<td>1.5</td>
</tr>
<tr>
<td>Insulation (cm)</td>
<td>8</td>
</tr>
<tr>
<td>Heating</td>
<td>Unheated</td>
</tr>
</tbody>
</table>

#### Crude

<table>
<thead>
<tr>
<th><strong>ESPO</strong></th>
<th><strong>Origin</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>light</td>
</tr>
<tr>
<td>API</td>
<td>34</td>
</tr>
<tr>
<td>μ (cP) @ 38°C</td>
<td>5.1</td>
</tr>
<tr>
<td>Pour point (°C)</td>
<td>-36</td>
</tr>
</tbody>
</table>

#### Conditions

<table>
<thead>
<tr>
<th><strong>ESPO</strong></th>
<th><strong>Winter T (°C)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet oil T (°C)</td>
<td>-6 to 10</td>
</tr>
</tbody>
</table>

Eastern Siberia-Pacific Ocean (ESPO)

Ref. news.bbc.co.uk (2006)

Russia Oil Pipeline Network

Huge pipeline network mainly developed for conventional oil. Challenge: Shift to heavier feedstock using existing infrastructure.

Questions addressed:
- Is it possible to use pipeline as originally designed to transport heavier oil?
- What drag reduction strategy to use?

Ref. news.bbc.co.uk (2006)
Drag Reduction Strategies

Most widely used methods:

A. Temperature conservation and heating
   - Passive: insulation, burial
   - Active: heating (Continuous or Point Heating)

A. Dilution with light hydrocarbons

B. O/W Emulsification

C. Others: drag reduction additive, low friction coatings, etc.

Pipe capacity fully used to transport oil

Up to 30% of water or diluent: ↓ Throughput

Cost, Stability (under development)
Case study: Transport of Heavier Oils

• Pipeline Section based on China-Russia Pipeline.
• Hypothesis: Shift to heavier feedstock
• To meet the max $\Delta P$ requirement:
  a) Reduction in throughput (x)
  b) Drag reduction—enable transportation without ↓throughput

• Thermal strategy for drag reduction – **Point heating**:
  I. Passive (Insulation, burial)
  II. Heating at section inlet (processing terminal, pumping station – available resources)
  III. Point heating at intermediate locations between pumping stations
   – Constraint: Maximum allowable oil temperature: $90^\circ C$
**Modelling Approach**

**First-principles model for a buried, insulated pipeline**

Evaluation of heat losses and $\Delta P$ along unheated pipeline sections

\[
-\frac{dP}{dz} = \frac{1}{2D_{w,i}} f\rho_{oil}u_{oil}^2 = \frac{4\tau_w}{D_{w,i}}
\]

\[
0 = \frac{1}{r} \frac{\partial}{\partial r} \left( r\lambda_{ins} \frac{\partial T_{ins}}{\partial r} \right)
\]

\[
\dot{m} = \pi R_{w,i}^2 \rho u
\]

\[
\pi \frac{D_{w,i}^2}{4} \rho_{oil} u_{oil} c_{p,oil} \frac{T_{oil}}{\partial z} = \pi D_{w,i} (-q''_{\text{losses}} + q''_{\text{friction}})
\]

\[
q''_{\text{env}} = \frac{1}{R_{ins,o} \cosh^{-1}(\delta/R_{ins,o})} \lambda_{\text{ground}} (T_{ins} |_{r=R_{ins,o}} - T_{env})
\]

\[
C_p, \rho, \mu, k f (\text{API, MeABP, } v_0, T)
\]
Case study: Transport of Heavier Oils

Definition of Pipeline Section

- Section of pipeline between two pumping stations
- Characteristics based on China-Russia Pipeline
- **Maximum** $\Delta P$ calculated based on:
  - ESPO crude oil ($\nu_{38^\circ C} = 5.11$ cSt, very low viscosity)
  - Worst cooling conditions ($T_{\text{env}} = -40^\circ C$)
  - $L = 300$ km
  - Max. Flowrate = 15Mton/yr

$\Delta P_{\text{max}} = 4.8$ MPa
Case study: Transport of Heavier Oils

Shift to heavier feedstock

<table>
<thead>
<tr>
<th>Oil</th>
<th>API</th>
<th>$v_{38^\circ C} \text{ (cSt)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESPO</td>
<td>34</td>
<td>5.1</td>
</tr>
<tr>
<td>1</td>
<td>24</td>
<td>120</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>150</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>250</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>450</td>
</tr>
</tbody>
</table>
Case study: Transport of Heavier Oils

I. Insulation (√)

II. Inlet Heating (up to 90°C)

- Enables transport for viscosity ≤ Oil 1 w/o ↓throughput.
- For more viscous oils: ↓throughput

E.g. Oil 3:
- 36 km short for full throughput
- 8.8% ↓throughput required to reach 300km

<table>
<thead>
<tr>
<th>Oil</th>
<th>ESPO</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_{38°C}) (cSt)</td>
<td>5.1</td>
<td>120</td>
<td>150</td>
<td>250</td>
<td>450</td>
</tr>
<tr>
<td>Inlet oil T [°C]</td>
<td>2</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>Throughput Loss [%]</td>
<td>0</td>
<td>2.7</td>
<td>8.8</td>
<td>15.4</td>
<td></td>
</tr>
</tbody>
</table>

Alternatively, Intermediate Heating
I. Insulation (√)
II. Inlet heating (√)

III. Intermediate heating

Decision variables:
- Number of heating stations
- Location
- Heat input in each station (ΔT)

Constraints: Max Oil Temperature (90°C)

Objective:
- Maximum throughput ($) 
- Minimum Heat Input (energy efficiency, $) 
- Other considerations: Practicality, maintenance
Case study: Transport of Heavier Oils

I. Insulation (√)
II. Inlet heating (√)

III. Intermediate heating
A. Single Point Heating at Midpoint

Example: Oil 3
a) Inlet heating only:
   8.8% throughput loss
b) Intermediate heating:
   Oil re-heated to 90°C (constraint)
   4.5% reduction throughput loss
I. Insulation (√)
II. Inlet heating (√)

III. Intermediate heating

A. Single Point Heating at Midpoint
   - Economic trade-off$^1$
     + Savings in throughput
       Loss of 1% of throughput: $52.9$MM/yr
     - Cost of heating
       Cost of increasing 10°C: $2.7$MM/yr (natural gas)
       + capital cost + maintenance

Subject to the cost of the heating technology, **cost of throughput generally dominant**

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Case study: Transport of Heavier Oils

I. Insulation (√)
II. Inlet heating (√)

III. Intermediate heating

A. Single Point Heating at Midpoint
   - Economic Trade-off:
     Throughput vs. Heat input
   - Oil 2: Max Throughput by heating to ≈ 86°C
     (room for further retrofit)
   - More viscous oils:
     - Heat to 90°C
     - Loss in throughput

-1% throughput = $52.9MM/yr
ΔT of 10°C = $2.7MM/yr +
Case study: Transport of Heavier Oils

I. Insulation (√)
II. Inlet heating (√)

III. Intermediate heating
   A. Single Point Heating: Optimal Location

   - Oil 2: Max Throughput and minimum $\Delta T$
   - More viscous oils:
     Optimal location for throughput near pipe midpoint

   -1% throughput = $52.9$MM/yr
   $\Delta T$ of $10^\circ C$ = $2.7$MM/yr +
Case study: Transport of Heavier Oils

I. Insulation (√)
II. Inlet heating (√)

III. Intermediate heating

B. Multiple Point heating

- Uniform distribution along the pipeline (location and heat duty).
- Temperature maintained to higher values → ↓viscosity, ↓ΔP
Case study: Transport of Heavier Oils

I. Insulation (√)

II. Inlet heating (√)

III. Intermediate heating

B. Multiple Point heating

- Same ΔT → same throughput as Case A (single heating, middle point)

- Permits greater heat input (ΔT) than single point heating (Max Oil T constraint).
I. Insulation (√)

II. Inlet heating (√)

III. Intermediate heating

Comparison

Minimum throughput loss for various retrofit options:

<table>
<thead>
<tr>
<th>Oil</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>No int. heating</td>
<td>0</td>
<td>2.7</td>
<td>8.8</td>
<td>15.8</td>
</tr>
<tr>
<td>1 int. Heating (A-E)</td>
<td>-</td>
<td>0</td>
<td>4.5</td>
<td>10.6</td>
</tr>
<tr>
<td>2 Int. heating (F)</td>
<td>-</td>
<td>-</td>
<td>3.3</td>
<td>9.2</td>
</tr>
<tr>
<td>3 Int. heating (G)</td>
<td>-</td>
<td>-</td>
<td>2.7</td>
<td>8.5</td>
</tr>
</tbody>
</table>
Importance of Insulation

ESPO Oil, why insulation in actual design?

- Insulated (actual) vs. non-insulated (still buried).
Case study: Transport of Heavier Oils

Importance of Insulation

ESPO Oil, why insulation in actual design?

Non-insulated:

- Pressure drop is manageable (drag reduction not an issue)
- Oil T approaches wax appearance temperature (WAT)

Insulation → Flow Assurance (avoid deposition and blockage)
Importance of Insulation

Retrofit for transportation of heavier oils

Example: Oil 3

Insulation: 4.5% Throughput loss

No Insulation: 23.5% Throughput loss

Non-insulated → Dramatic T drop:

↑↑ ΔT required
↓ Throughput
Case study: Transport of Heavier Oils

Importance of Insulation
Thermal retrofits of heavier oils

Non-insulated:
↑↑ ΔT required
↓ Throughput

+ Insulation

<table>
<thead>
<tr>
<th>Case</th>
<th>L/4</th>
<th>L/3</th>
<th>L/2</th>
<th>2L/3</th>
<th>3L/4</th>
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<tbody>
<tr>
<td>A</td>
<td>ΔT</td>
<td></td>
<td>ΔT</td>
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<td>ΔT</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td>ΔT</td>
<td></td>
<td>ΔT</td>
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<tr>
<td>C</td>
<td></td>
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<td>ΔT</td>
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<td>ΔT</td>
</tr>
<tr>
<td>D</td>
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<td>ΔT/2</td>
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<tr>
<td>E</td>
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<td>ΔT</td>
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<td>ΔT</td>
</tr>
<tr>
<td>F</td>
<td>ΔT/3</td>
<td>ΔT/2</td>
<td></td>
<td>ΔT</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>ΔT/3</td>
<td></td>
<td>ΔT</td>
<td></td>
<td>ΔT</td>
</tr>
</tbody>
</table>

L=300km

Workshop Energy and Water Security
Qatar
Case study: Transport of Heavier Oils

Importance of Insulation

Purpose of Insulation

ESPO ➔ Flow Assurance

Heavier oils ➔ • Throughput savings
• Energy efficiency

Recommended in pipeline design for cold environments.
Conclusions

- Point/Multipoint heating strategy can be used to retrofit existing pipelines, design for light oil, to transport heavy oil and minimize throughput losses.

- Best heating strategy depends on oil type.
  When carry out a retrofit:
  a) Look for optimal economic/energy design for the case on hand.
  b) Avoid bottlenecks that might limit application for heavier feedstock.

- Insulation recommended in initial design.

- For this method to be advantageous: Heating technology featuring:
  - Adaptable design (set-up, dismantling, retrofit).
  - Low capital cost.
  - Small impact on existing facilities.