Natural gas compression performance calculations

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Overview

- Two topics:
  - Gas hydrates
  - Sub-ambient flow in pipelines

- Principles of gas compression
Two topics
Two topics

- Gas hydrates
- Sub-ambient flow in pipelines
Gas hydrates

- Besides posing problems for flow assurance gas hydrates in the future could be a source of NG fuel
- Several research programs target their economic extraction
Sub-ambient pipeline flow

- Is it possible for a pipe to transmit fluids at sub-ambient pressure i.e. below atmospheric pressure?

- Pressure drop ($\Delta p$):

\[ \Delta p = p_1 - p_2 = \frac{128 \mu \ell Q}{\pi D^4} \]

- A pressure differential drives flow. Therefore, $p_2 < p_1$
Major pump needs in an LNG facility

- Amine circulation
- Scrub column & fractionation towers
- LNG product pumps & loading pumps
- Seawater pumps (if seawater cooled)
- Hot oil pumps
- 2-4 pumps per LNG tank
Gas compression performance
Definitions

- Pressure ($P$) is the direct force per unit area normal to the surface
  \[ P = \frac{F}{A} \]

- **Absolute pressure** ($P_{\text{abs}}$) is measured relative to absolute vacuum (absolute zero pressure)

- **Gage pressure** ($P_G$) is the difference between absolute & atmospheric pressure

- **Vacuum pressure** is below atmospheric

- An **ideal gas** is an imaginary substance which obeys $PV=RT$
More definitions

- **Incompressible substance** is the one whose specific volume (or density) remains constant when subject to a pressure.

- A **reversible process** can be reversed w/o leaving any trace on the surroundings. Net heat & net work exchange btw stm&surroundings = 0

- **Enthalpy** is the *thermodynamic potential* of a system denoted by $h$ (units: $J$ or BTUs):

$$h = u + P\nu$$
Compression performance

- Interested in calculating:
  - Compressor head (inlet & outlet pressure)
  - Discharge temperature
  - Compressor efficiency
  - Sizing of compressor (hp)
Gas-turbine driven centrifugal compressor
Reversible isothermal gas compression

- Purpose of compression: mechanical work raises gas suction pressure to higher discharge pressure
- Reversible shaft work of a compressor, \( w_s \), for open process for \( P_1 \) to \( P_2 \)

\[
 w_s = -\Delta h = - \int_{P_1}^{P_2} v dP, \tag{1}
\]

where: \( h = \) enthalpy, \( h = u + pv \)
\( v = \) specific volume \((m^3/kg \text{ or } ft^3/lb)\)
-ve sign indicates that work is being done on the compressor
- Since \( V = RT/P \), for an isothermal process the reversible shaft work of an ideal gas is:

\[
 w_s = -RT \ln(P_2/P_1)/MW, \tag{2}
\]

where: \( R = \) gas constant \((Nm/kg \cdot K \text{ or } Btu/lbmol \cdot R)\), \( MW = \) molec. weight
Reversible **adiabatic** heat transfer

- Heat transfer from compression into fluid
- Thermal energy absorbed by the gas phase
- Polytropic process:
  \[ P V^n = C \]  \hspace{1cm} (3)

- $\gamma$ is the *polytropic exponent*; $C = \text{constant}$
Adiabatic work done on compressor:

\[ w_s = \frac{\gamma RT_1}{MW(\gamma - 1)} \left[ 1 - \left( \frac{P_2}{P_1} \right)^{(\gamma-1)/\gamma} \right] \]  \hspace{1cm} (4)

Ratio \( (P_2/P_1) \) is the compression ratio

\( T_i \): inlet temperature. The specific heat ratio, \( \gamma \), is:

\[ \gamma = \frac{C_P}{C_V} = \left[ \frac{C_P}{C_P - R} \right] \]  \hspace{1cm} (5)

Since \( R = C_P - C_V \)

Where \( C_P \) is specific heat @ constant pressure &

\( C_V \) the specific heat @ constant volume [of the gas]
Outlet compressor temperature

- For a reversible adiabatic compression of an ideal gas, outlet temp:
  \[ T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}}. \]  
  \[ (6) \]

- Empirically, \( T_2 \) can be obtained from:
  \[ T_2 = T_1 \left( 1 + \left( \frac{P_2}{P_1} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right) / \eta_{IS}, \]  
  \[ (7) \]

- \( \eta_{IS} \) is the entropic efficiency with heat losses. Thus:
  \[ P_v^\kappa = C \]  
  \[ (8) \]

\( \kappa \) is the polytropic constant (empirically obtained)
Outlet compressor temperature

- $\kappa$ replaces $\gamma$ in eqn (7):

\[
W_s = \frac{\kappa RT_1}{MW(\kappa - 1)} \left[ 1 - \left( \frac{P_2}{P_1} \right)^{(\kappa-1)/\kappa} \right].
\]

- If $\kappa$ is not known, $\gamma$ can be used.
- Assumption: all gas components behave like an ideal gas.
- Using eqns (1)-(9) we can determine:
  - Isothermal work to compress a gas from pressure ($P_1$) into ($P_2$)
  - Adiabatic work to compress a gas from pressure ($P_1$) into ($P_2$)
  - Discharge temp. for adiabatic compression
- Example #1
Multi-stage compression

- Multi-staging: final pressure is attained by more than one stages/steps
- Reasons for multi-staging:
  - Cool the gas btw stages thereby increasing efficiency by decreasing gas volume & work.
  - Material limitations. 150°C limit for construction materials, seals, lubricants.
  - Recommended temp. decreases with high pressure
- Limiting temps define compression ratios to btw 3:1 to 5:1
- Min work when each stage does same amount of work (~press ratio/stage)
- Pressure ratio (PR):

\[
PR = (P_2/P_1)^{1/m}
\]  

(10)

- \( m \) = number of stages
- Example #2
Compressor efficiencies

- **Reversible adiabatic (or isentropic efficiency),** $\eta_{IS}$:
  \[ \eta_{IS} = \frac{W_s}{W_{s,\text{ACTUAL}}} \] (11)

- $W_s$ is determined from eqn (4)

- Centrifugal compressors’ efficiency given by **polytropic efficiency**, $\eta_P$:
  \[ \eta_P = \frac{(\gamma-1)/\gamma}{[(\kappa-1)/\kappa]} \] (12)

- Polytropic efficiency > adiabatic efficiency.

- Discharge conditions can also be determined from:
  \[ T_2 = T_1 \left( \frac{P_2}{P_1} \right)^{(1/\eta_P)(\gamma-1)/\gamma} \] (13)

- $\eta_P$ is the polytropic efficiency

**Example #3**
Capacity & power calculations

- Compressibility factor, \( Z \), is:

\[
Z = \frac{P_v}{RT} \tag{14}
\]

- \( Z \) is due to gases deviating from ideal gas law. \( Z = \frac{V_{actual}}{V_{ideal}} \)

Power Requirements
- For isentropic compression & efficiency:

\[
Power = \dot{m} \cdot z_{avg} \cdot w_s \tag{15}
\]

- \( \dot{m} \) is the mass flow rate; \( z_{avg} \) is the average of the inlet & outlet compressibility factors
Reciprocating compressors

- Power estimation:

\[
\text{Brake HP} = 22 F \text{ PR} m \text{ MMacfd} \quad (16)
\]

- Brake HP is work delivered to compressor, \( F \), correction factor:
  - For single stage (\( m=1 \)), \( F = 1.0 \)
  - For double stage (\( m=2 \)), \( F = 1.08 \)
  - For three-stages (\( m=3 \)), \( F = 1.10 \)

- PR = pressure ratio; HP = horsepower; \( m \) = # of stages

- Vendors rate compressors on 14.4 psi [for simplicity] than 14.7 psi

- Equation 16:
  - Developed for large, slow-speed compressors of 300-400 rpm
  - Gases with \( \text{SG}=0.65 \) & \( \text{PR}>2.5 \)
  - For \( 0.8<\text{SG}<1.0 \), use 20 in eqn (16), if \( \text{SG}<0.8 \) use 22
Flow rate

- Volumetric flow rate (Q) given by:

\[ Q = \text{scfm} \left( \frac{14.7}{P_i \text{ (psia)}} \right) \left( \frac{T_i \text{ (°R)}}{520} \right) \left( \frac{z_i}{z_R} \right) \]  

(17)

- Where “1” & “R” denote inlet & reference conditions. Reference state: 14.7 psia @ 60°F (15.6°C); scfm standard cubic feet

- Example #4
## Compressor efficiencies

**TABLE 4.2**

Typical Cost Effective Ranges of Compressors Used in Gas Processing

<table>
<thead>
<tr>
<th>Inlet Flow Rate(^a) acfm (m(^3)/h)</th>
<th>Maximum Pressure psig (barg)</th>
<th>Isentropic Efficiency, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Inlet</td>
<td>Discharge</td>
</tr>
<tr>
<td>Reciprocating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single stage</td>
<td>1 - 300 (2 - 500)</td>
<td>No limit</td>
</tr>
<tr>
<td>Multistage</td>
<td>1 - 7,000 (2 - 12,000)</td>
<td>No limit</td>
</tr>
<tr>
<td>Centrifugal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single stage</td>
<td>50 - 3,000 (80 - 5,000)</td>
<td>No limit</td>
</tr>
<tr>
<td>Multistage</td>
<td>500 - 200,000 (800 - 350,000)</td>
<td>No limit</td>
</tr>
<tr>
<td>Oil-free rotary screw</td>
<td>&lt;40,000 (70,000)</td>
<td>&lt;150 (10)</td>
</tr>
<tr>
<td>Oil-injected rotary screw</td>
<td>&lt; 10,000 (20,000)</td>
<td>&lt; 400 (30)</td>
</tr>
</tbody>
</table>

\(^a\) Compressor-gas volumes are based upon actual gas volumes at suction temperature and pressure.
Thanks for your attention!