CFD Analysis of Oil Flooded Twin Screw Compressors

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Introduction

- Oil Injection
  - Cooling of gas during Compression
  - Sealing of the leakage gaps
  - Lubrication

- Oil losses
  - Viscous friction power loss
  - Oil drag and momentum loss

- Optimum quantity and timing.

- Oil injection temperature and residence time

- Spray formation, droplet diameter and spread.

- Optical visualization inside oil injected compression chambers.

- Design improvements demand for CFD modeling

Oil power loss contributions in leakages
(Deipenwisch and Kauder, 1999)
Multiphase CFD Modelling

- Characterization of multiphase flow regimes based on the various coupling effects between the continuous and the dispersed phases

  - Eulerian – Lagrangian
    - dispersed phase quantity very low, the phase particles are very fine with negligible momentum
    - compressed gas treated as continuous phase and oil droplets as particles in the Lagrangian frame
    - one-way, two-way and turbulence couplings possible

  - Eulerian – Eulerian
    - condition of heavily oil flooded operation
    - in addition to the oil droplets, oil film on the rotor and housing
    - the pressure field is shared by the phases and independent momentum equations
Volume loading – dilute or dense

» Refers to the volume fraction of secondary phase(s)

\[
\text{Volume Fraction} = \alpha = \frac{\text{Volume of the phase in a cell}}{\text{Volume of the cell}}
\]

» For dilute loading (< 10%), the average inter-particle distance is around twice the particle diameter. Thus, interactions among particles can be neglected.

Particulate loading – ratio of dispersed and continuous phase inertias

\[
\frac{\alpha_{\text{particle}} \rho_{\text{particle}}}{\alpha_{\text{continuous}} \rho_{\text{continuous}}} = \begin{cases} 
<< 1, & \text{one way coupling} \\
\approx 1, & \text{two way coupling}
\end{cases}
\]
Oil Injected Screw Compressor Modelling

- Thermodynamic Chamber Model

Oil droplets are assumed to have a mean Sauter diameter and the heat exchange between the spherical droplets and the gas via convection can be balanced with the droplet temperature rise.

\[
\frac{dT_{oil}}{d\theta} = \frac{h_{oil}A_{oil}(T_{gas} - T_{oil})}{\omega m_{oil}c_{oil}}
\]

Using, \( Nu = 2 + 0.6 Re^{0.6}Pr^{0.33} \), heat transfer coefficient for Stokes flow

\[
T_{oil} = \frac{T_{gas} - k T_{oil,\infty}}{1 + k}
\]

\[
k = \frac{\omega d_s c_{oil}}{6h_{oil} \Delta \theta}
\]

constant \( k \) is the non-dimensional time constant of the droplet.

Dilute Volume Loading

Discharge Port and Pipe chamber Temperature

Suction Port Closed

Discharge Port Open

Oil Temperature

Equilibrium

Gas Temperature

Oil Injection

Compression

Suction Port and Pipe chamber Temperature
Oil Injected Screw Compressor Modelling

- Simplified CFD Model

\[
\frac{\partial}{\partial t} \int_\Omega \rho \phi d\Omega + \int_S \rho \phi \mathbf{v} \cdot \mathbf{n} dS = \int_S \Gamma \text{grad} \phi \cdot \mathbf{n} dS + \int_\Omega q_\phi d\Omega
\]

Energy Source

\[ q_e = \frac{\rho c_p}{\partial t} (T_{gas} - T_{oil}) \]

Momentum Source

\[ q_u = \frac{1}{2} \frac{\rho}{\partial t} (|u| u) \]

Temperature Result under an energy source formulation

Local Viscosity Function

Locally Dense Volume Loading

Under prediction of flow under a local viscosity formulation

Air Flow (m³/min) vs. Speed (rpm)

- Experimental
- CFD
Oil Injected Screw Compressor Modelling

- Full CFD Model
- Eulerian – Eulerian treatment of the compressed gas and the injected oil
- Pressure field shared between the phases
- Independent $u,v,w$ - momentum conservation equation for each phase with interphase drag effects
- Volume fraction conservation ensures that sum is unity and mass exchange in case of phase change is accounted.
- Independent energy conservation equation with interphase heat transfer
- Homogeneous or Phase specific turbulence model
Eulerian Multiphase Model Equations

- **Continuity**:
  \[
  \frac{\partial (\alpha_q \rho_{q_q})}{\partial t} + \nabla \cdot (\alpha_q \rho_{q_q} \mathbf{u}_q) = \sum_{p=1}^{n} \dot{m}_{pq}
  \]

- **Momentum** for \( q \)th phase:
  \[
  \frac{\partial (\alpha_q \rho_{q_q} \mathbf{u}_q)}{\partial t} + \nabla \cdot (\alpha_q \rho_{q_q} \mathbf{u}_q \mathbf{u}_q) = -\alpha_q \nabla p + \alpha_q \rho_{q_q} \mathbf{g} + \nabla \cdot \mathbf{\tau}_q + \sum_{p=1}^{n} \left( \mathbf{R}_{pq} + \dot{m}_{pq} \mathbf{u}_q \right) + \alpha_q \rho_{q_q} \left( \mathbf{F}_q + \mathbf{F}_{\text{lift},q} + \mathbf{F}_{\text{vm},q} \right)
  \]

  - **Transient**
  - **Convection**
  - **Pressure**
  - **Body**
  - **Shear**
  - **Interphase mass exchange**
  - **External, lift, and virtual mass forces**

  *Solids pressure term is included for granular model.*

- The inter-phase exchange forces are expressed as:
  \[
  \mathbf{R}_{pq} = K_{pq} \left( \mathbf{u}_p - \mathbf{u}_q \right)
  \]

  **Exchange coefficient**

- **Energy** equation for the \( q \)th phase can be similarly formulated.
Grid Generation for Oil injected screw compressor

- Conformal single domain rotor mesh
- Method of Back ground blocking used to regularise cells
- Conformal single domain rotor mesh
- Conformal single domain rotor mesh
Case Study

- 4 lobed male and 5 lobed female rotors
- ‘N’ rotor profile, Male rotor drive
- Built in volume ratio 3.6
- Combined axial and radial suction
- Axial discharge ports
- Operating speed 3000 – 6000 rpm
- Operating pressure 3.0 – 11.0 bar
- Oil injection by discharge pressure
- Radial, Interlobe and End clearances 50 microns
## Measurements

**City University London Test Rig**

<table>
<thead>
<tr>
<th>Case</th>
<th>Speed (rpm)</th>
<th>Suction Pressure (bar)</th>
<th>Suction Gas Temperature (K)</th>
<th>Discharge Pressure (bar)</th>
<th>Oil injection Pressure (bar)</th>
<th>Oil Injection Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>1.00</td>
<td>298.0</td>
<td>6.0</td>
<td>5.5</td>
<td>323.0</td>
</tr>
<tr>
<td>2</td>
<td>3000</td>
<td>1.00</td>
<td>298.0</td>
<td>8.0</td>
<td>7.5</td>
<td>323.0</td>
</tr>
<tr>
<td>3</td>
<td>6000</td>
<td>1.00</td>
<td>298.0</td>
<td>8.0</td>
<td>7.5</td>
<td>323.0</td>
</tr>
</tbody>
</table>
CFD Model

- Eulerian – Eulerian two phase model
- Phase I – Air Ideal Gas
- Phase II – Constant property Oil
- First order discretisation
- CFX Solver

<table>
<thead>
<tr>
<th>Domain</th>
<th>Cell Structure</th>
<th>Node Count</th>
<th>Cell Count</th>
<th>Orthogonality Angle (Min)</th>
<th>Expansion Factor</th>
<th>Aspect Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor</td>
<td>Hexahedral</td>
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<td>406368</td>
<td>7.4</td>
<td>646</td>
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<td>Suction Port</td>
<td>Tetra + Hex</td>
<td>119058</td>
<td>203255</td>
<td>30.2</td>
<td>279</td>
<td>9</td>
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<tr>
<td>Discharge Port</td>
<td>Tetra + Hex</td>
<td>98521</td>
<td>253095</td>
<td>19.6</td>
<td>53</td>
<td>28</td>
</tr>
<tr>
<td>Oil Injection Port</td>
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<td>28340</td>
<td>25144</td>
<td>55.7</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>
Internal pressure rise is similar at all three operating conditions.
- At 3000 rpm when the discharge port opens, the flow pulsations in the port are low.
- At 8.0 bar discharge pressure and 6000 rpm the peak pressure reaches 10.0 bar, also visible in the contour plot.
- For 3000 rpm pulsations and the maximum pressure are both lower than at the higher speed.
Results - Flow and Indicated Power

- At 3000 rpm at both discharge pressures the gas flow prediction is within around 12% lower than the measured values, while at 6000 rpm and 8.0 bar discharge, the predicted flow is within 2% of measurements. From 3000 to 6000 rpm, the flow has increased by 85%.

- Indicated power at 3000rpm is calculated within 4% of the measurements while at 6000 rpm it is about 10% higher than the measured value.

- Power at 3000 rpm, 8.0 bar is 20% more than that at 6.0 bar. From 3000 to 6000rpm, indicated power increased by more than twice.

Experimental flow and power at 3000rpm, 6.0 bar discharge pressure used for normalization.
Results - Oil Injection

Interaction of Oil Injection with Gate rotor Lobes
The pulsating nature of the oil injection is visible.

Quantity of oil injected at 8.0 bar discharge is similar at both speeds 3000 rpm and 6000 rpm.

The oil flow rate at 6.0 bar is lower than at 8.0 bar discharge as it is controlled by the discharge pressure.

Iso-surface of oil volume fraction 0.1 shows an accumulation of oil in the rotor tips and also high concentration on the discharge port walls. Similarly oil accumulates in the interlobe gaps and is transported by the rotors. The oil distribution in the discharge port is unsteady but cyclically repeating.
Due the injected oil at 323 K, the gas temperature is substantially lowered and does not exceed 340 K.

At 3000 rpm and 8 bar discharge pressure, the peak temperature is about 10 degree lower than that at 6000 rpm. This is because the amount of oil injected at the same discharge pressure and different rotational speeds is almost the same in this model.

Lower residence time of the oil at higher speed results in lower heat transfer from gas to oil and results in a higher discharge temperature.

There is only a small difference in the gas temperature at the same speed and different discharge pressures because the quantity of oil injected at higher pressure increases.
Results - Gas Temperature

- Distribution of gas temperature at 8.0bar discharge pressure, 6000rpm with an iso-surface of oil volume fraction 0.1.
- Local maximum temperature 360 K.
- The gas temperature distribution is highly non-uniform.
- This non-uniformity is due to the non-homogeneous distribution of oil in the compression chamber.
Conclusion

CFD modelling approach for calculation of oil flooded screw compressor was tested. A single domain structured numerical mesh of the flow domain was required and was generated by SCORG.

- Test analysis showed a close match in the prediction of the mass flow rates of gas.
- The indicated power obtained by CFD predictions matched well with the measured shaft power.
- The mixing of the phases, distribution of oil, heat transfer between gas and oil and also effects on sealing due to high oil concentration in leakage gaps were well captured.
- Strong interaction of oil injection with the rotors, deposition on the rotor surface, discharge port walls and heavy accumulation in the interlobe region was observed.

In order to improve the model further it will be necessary to investigate impact of grid quality on the results and to test for higher accuracy solver settings along with the development of techniques for improving solver robustness.
Thank you
References


Deipenwisch R and Kauder K., (1999). Oil as a design parameter in screw type compressors: oil distribution and power losses caused by oil in the working chamber of a screw type compressor. IMECH Transactions; 6; 49-58; Int. Conf. on Compressors and their systems, London.


Stokes Number

- For systems with intermediate particulate loading, the Stokes number provides a guidance for selecting the most appropriate model.
  - The Stokes number, \( \text{St} \), is the ratio of the particle (i.e. dispersed phase) relaxation time (\( \tau_d \)) to the characteristic time scale of the flow (\( \tau_{\text{gas}} \)).
    \[
    \text{St} = \frac{\tau_d}{\tau_c}
    \]
    
    where \( \tau_d = \frac{\rho_d d_d^2}{18 \mu_{\text{gas}}} \) and \( \tau_{\text{gas}} = \frac{D}{U} \).
  - \( D \) and \( U \) are the characteristic length and velocity scales of the problem.
  - For \( \text{St} \ll 1 \), the particles will closely follow the flow field.
  - For \( \text{St} > 1 \), the particles move independently of the flow field.
Results - Oil Injection