Thermal Acoustic Oscillation: Causes, Detection, Analysis and Prevention

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TAO Occurs

- **Slender Half Tube**
  - Closed at warm end (or slight flow)
  - Open at cold end (either in vapor or liquid)
- **Spontaneous**
- **Critical temperature ratio needed to initiate TAO**
- **TAO transfers heat from the warm end to the cold end because gas absorbs heat from the walls as it expands at the warm end and gives up heat to the walls as it is compressed at the cold end**
- **Can increase heat transfer 1-3 orders of magnitude over that of conduction**
TAO Process

- Cold gas enters the warm end and rapidly expands
- Expanding gas pushes warmed gas into the cold open end
- Inertial forces cause a low pressure to form in warm end
- The low pressure causes the flow to reverse
- Cold dense gas moves into warm end
- Creates large radial temperature gradient
- Cold gas gets heated
- Process repeats
- Ref. 5
TAO Happens

- Cryogenic Boil Off Reduction System
  - Unexplained heat
  - Oscillation observed with high-speed pressure-transducer
TAO Frequency

- Tube acts as $\frac{1}{4}$ wavelength acoustic resonator
- $f = \frac{c}{\lambda}$
  - $\lambda$ is the $4 \times \frac{1}{4}$ wavelength tube, for lowest frequency
    - without liquid in the tube
  - $c$ is the speed of sound at vapor temperature

- Example
  - Hydrogen at 20K, $R = 4124\, J/kgK$, $k = 1.41$
  - $c = 341\, m/s$
  - $\lambda = 4m$
  - $f = 85s^{-1}$
Where TAO Does Not Occur

- **Closed system**
  - e.g. between two valves
  - Can occur after a valve is open
- **Open at both ends**
  - e.g. an open vent
  - Very small openings may appear as closed
- **Small ratios of $T_{\text{hot}}/T_{\text{cold}}$**
  - e.g. $\alpha < 8$ for a 1m long tube
  - $300K/20K = 15$
- **Very small inside diameter tubes**
  - e.g. ID < 0.015” for a 1m long tube
Typical Analytical Model

\[ \alpha = \frac{T_h}{T_c} \]
\[ \xi = \frac{L_h}{L_c} \]

WARM CLOSED END

COLD OPEN END

CRYOGENIC FLUID

Temperature Step Change

Liquid Helium
The Equations

- Solution of TAO stability curves depends on solution of combined mass, momentum, energy for a compressible fluid:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} = 0
\]

\[
\rho \frac{\partial \mathbf{v}}{\partial t} = -\nabla P + \frac{F_B}{\rho} + \mu \nabla^2 \mathbf{v} \quad (2D)
\]

\[
\rho C_P \frac{\partial T}{\partial t} = -\nabla \cdot q + \frac{\partial \ln V}{\partial \ln T} \left| \frac{dP}{dt} - \tau \cdot \nabla \mathbf{v} + S \right.
\]

\[
P = Z \rho RT
\]

- Standard method of solution is a perturbation solution about the mean value for \( \rho, u, v, P, T \):

- Example: \( P = P_m + \hat{P}_1 \epsilon + \hat{P}_2 \epsilon^2 + \ldots \)

- If a sinusoidal wave is assumed, \( P = P_m + \hat{P}_1 \epsilon + \hat{P}_2 \epsilon^2 + \ldots \) only the first order term is retained, because \( P_m = 0 \) and higher order terms are small.

\[\therefore P = \epsilon \hat{P}_1 \exp(i\omega t), u = \epsilon u_1 \exp(i\omega t), etc. \quad \text{Real part of } \omega \text{ is oscillation frequency}\]

- Substitute perturbed solutions into 5 equations, solve numerically
TAO Critical Conditions

\[ \alpha = \frac{T_{\text{hot}}}{T_{\text{cold}}} \]

\[ \xi = \frac{L_{\text{hot}}}{L_{\text{cold}}} \]

Gu & Timmerhaus
University of Colorado

Open end above liquid
Temperature step change

\[ L_{\text{tube}} = 1 \text{m} \]

N.B.P. parahydrogen

TAO Occurs

No TAO
Effect of Changing Tube Size

- Example
  - $L = 1\text{m}$
  - Tube: 0.25 OD
    - 0.032” wall
  - $\alpha = 15$
    - 300K/20K = 15
  - $\xi = 5$
  - Could make stable by:
    - Increasing tube size (weak: requires big change)
    - Increasing $\xi$
    - Decreasing $\alpha$
Effect of Length Ratio $< 1$

$\xi > 1$  Open end in vapor  $\xi < 1$

$\xi = 1$
$\xi = 3$
$\xi = 5$
$\xi = 9$
$\xi = 19$

Open end above liquid
$T$ step change
$L_{\text{tube}} = 1\text{m}$
N.B.P. parahydrogen

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Dry vs Wet Open End

Open End in Vapor

Open End in Liquid

T.P. parahydrogen, $L_{\text{tube}}=1\text{m}$, Step change

Mass of liquid in tube will lower the oscillation frequency

$\xi < 1$ have little effect

Open end 0.1m below liquid surface

LN$_2$, Ar, LOX
Effect of Thermal Gradient

- Reducing temperature gradient raises temperature ratio needed to initiate TAO
- Step change is worst case
- Insulation is useful to linearize the temperature distribution

\( \xi = 1 \)
\( L = 1 \)

When temperature gradient is linear, a temperature ratio of 15 is stable for all tube sizes

\( \frac{T}{T_0} \)
\( \frac{X}{L} \)
\( 10^4, 10^3, 10^2, 10^1, 10^0 \)

\( 300K/20K \)
Dipping Effects

- Adjust
- Liquid He, H₂, O₂, Ar, N₂
- Dipping Depth
Dipping Effects

- LH2 did not enter tube until submersed 20cm
  - Ref. 4

Note difference in behavior between He and H2. Use caution when applying He findings to H2 applications.
TAO Forces

- **Forces in TAO**
  - **Driving force**
    - Temperature ratio and gradient
    - Heat transfer area
      - Length and radius of warm section
      - ‘Driving force is directly proportional to warm end tube length’
  - Viscous resistance
    - Viscosity in warm section predominates when $\xi > 1$
    - Length ratio critical
  - Inertial force
    - Oscillating Mass
    - Pressure, temperature, volume
- **Features**
  - More easily excited when cold end is in fluid
  - Lower frequency when fluid is in fluid
To increase stability

- Reduce temperature gradient
  - $\alpha_{\text{min}} = 5$ (end not in liquid)
  - $\alpha_{\text{min}} = 2$ (end in liquid)
- Increase length ratio
  - Applies to right hand region
  - Increase $L_{\text{hot}}$
  - Decrease $L_{\text{cold}}$

N.B.P. para-hydrogen  $L=1\text{m}$
Open end not in liquid
Changing Tube Size or Temperature Ratio

\[ g68 \quad \xi = \frac{T_{\text{hot}}}{T_{\text{cold}}} \]

\[ g91 \quad \xi_{\ell} = \frac{L_{\text{hot}}}{L_{\text{cold}}} \]

- Increase inertial damping
- Increase radius
- Large diameters required
- Might not be practical

- Increase viscous damping
- Decrease radius

- Increase or decrease temperature ratio

Examples:
@ O \( \xi = 1 \)
@ B \( \xi = 1 \)
@ E \( \xi = 1 \)
@ F \( \xi = 1 \)

Open end above liquid
T step change
\( L_{\text{tube}} = 1 \text{m} \)
N.B.P. parahydrogen
Mitigation Methods

- Reduce driving force
  - Change temperature ratio $\alpha$
    - Reduce temperature gradient
    - Make warm end colder
      - Insulation
  - Change length ratio $\xi$
    - Make warm end shorter
      - Reduces driving force
- Increase viscous damping
  - Reducing tube radius
    - e.g. add restrictor to cold end
- Increase inertial damping
  - Increase tube radius
  - Change temperature gradient
    - Insulation
- Block line
  - Check valve
  - Add filter
    - Use as acoustic absorber
- Connect Fill with Vent
- Resonator
  - Add resonator to warm end
  - Works theoretically
- Parallel $\frac{3}{4}$ wavelength tube
- Other
  - Get away from $\xi = 1$
  - Adding a large cavity to warm end can have the same effect as opening the closed end
    - e.g. add a vent
  - Get open end out of liquid
    - Raises minimum critical temperature ratio
  - Fill tube with liquid
    - Oscillations would need to drive a large mass
    - e.g. add vent to warm end of dip tube
Possible Fix: Vent Hole

- Change effective length of dip tube by allowing liquid to fill it
  - Drill hole in warm end
  - Effective when tank is relatively full in 1g
  - When fluid level is low, vapor length will increase and TAO may return
Actual Fix: Cross Over Valve

Ref. 7
If a $\frac{1}{4}$ wave-length tube and a $\frac{3}{4}$ wave-length tube are in parallel, their out of phase oscillations will cancel each other.
Warm End Resonator

Shown to work theoretically

Ref. 1
Check Valve

Good location
Tube terminated at
low temperature

Insulation Boundary
References

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8. J. Hartwig, Thermal Acoustic Oscillation Analysis, NASA GRC