THERMAL ACOUSTIC OSCILLATION:
CAUSES, DETECTION, ANALYSIS, AND PREVENTION

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ABSTRACT

Thermal Acoustic Oscillations (TAO) can occur in cryogenic systems and produce significant sources of heat. This source of heat can increase the boil-off rate of cryogenic propellants in spacecraft storage tanks and reduce mission life. This paper discusses the causes of TAO, how it can be detected, what analyses can be done to predict it, and how to prevent it from occurring. The paper provides practical insight into what can aggravate instability, practical methods for mitigation, and when TAO does not occur. A real life example of a cryogenic system with an unexpected heat source is discussed, along with how TAO was confirmed and eliminated.

INTRODUCTION

Thermal acoustic oscillations (TAOs) can spontaneously occur in cryogenic systems when there is a large thermal gradient along the length of a gas filled tube which is closed at the warm end. These TAOs can pump large amounts of heat and significantly increase the magnitude of heat leak being transferred by the tube. “This oscillatory heat leak (can) be ten to a thousand times greater than the normal conductive heat leak into the system” [1]. TAOs are typically observed in piping that feeds cryogenic reservoirs, such as the fill tube for the cryogenic Dewar shown in Figure 1. Similar arrangements can be found in cryogen storage vessels, such as liquid hydrogen (LH_2) and liquid oxygen (LOX) storage tanks on spacecraft.

CAUSES

TAOs occurs when cold gas enters the warm section of the tube and expands. The expansion pushes warm gas into the cold section where the gas contracts. The inertia of the gas moving away from the warm section creates a low pressure in the warm section. This is aggravated by the high density and therefore high mass of the gas in the cold section which is being pushed away from the warm section. At low temperatures, the viscosity of the gas decreases; therefore there is a slug of high density gas, with low viscosity acting like a mass attached to a spring, as depicted by the mass-spring representation shown in Figure 2. The low pressure causes the flow direction to reverse, the cold gas re-enters the warm section, and the process repeats. The expansion in the warm section is followed by contraction in the cold section, which causes heat to be transferred.

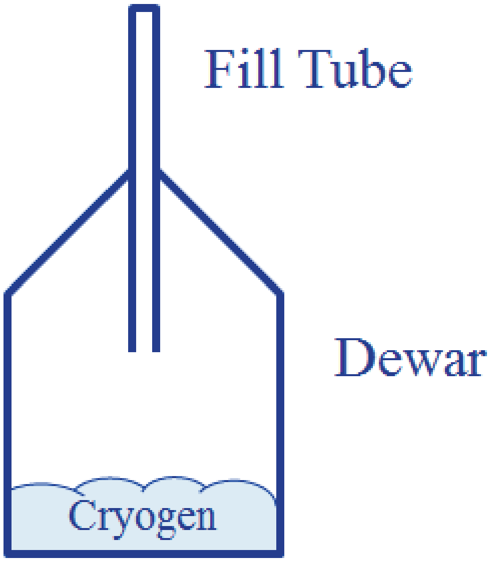


Figure 1, Classic Place for Thermal Acoustic Oscillations to Occur.

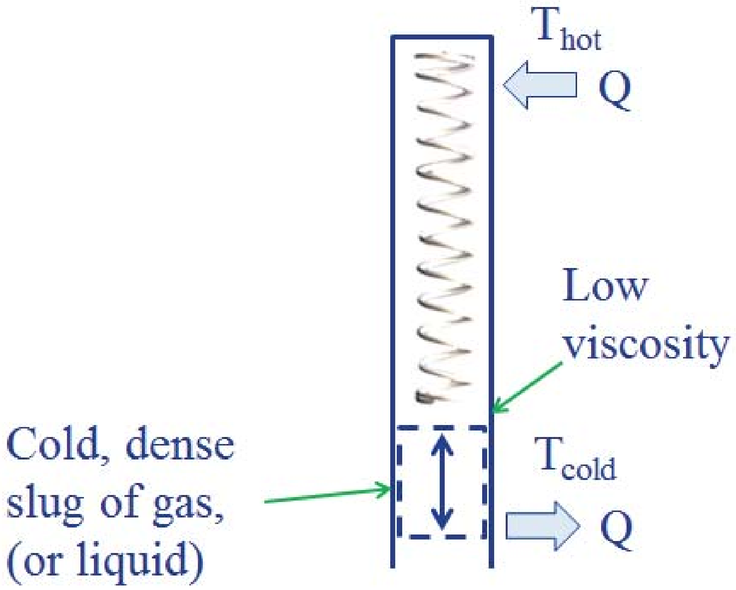


Figure 2, Mass-spring Representation.

TAO occurs in a half-tube, i.e. closed at one end and open at the other. Therefore TAO does not occur between two valves but can occur after one valve is open. It also does not occur when both ends are open, e.g. an open vent line; although, very small openings could appear as being closed. TAO only occurs when there is a large temperature difference between the cold and warm end. Also, TAO does not occur in very small diameter tubes.

DETECTION

During testing of the Cryogenic Boil-Off Reduction System (CBRS) at Glenn Research Center, unexplainably high boil-off of liquid hydrogen was occurring. It was proposed that TAOs were occurring, most likely in the fill/drain tube, which is shown in Figure 3. To verify this, a high speed pressure transducer was installed in the supply piping for the fill/drain tube, and a cross-over valve was installed between the fill/drain tube and the vent. The function of the pressure transducer was to measure oscillations in the pressure, if they were occurring, and if they were occurring and being caused by TAO, then opening the cross-over valve should eliminate them, by making the closed-end an open-end.

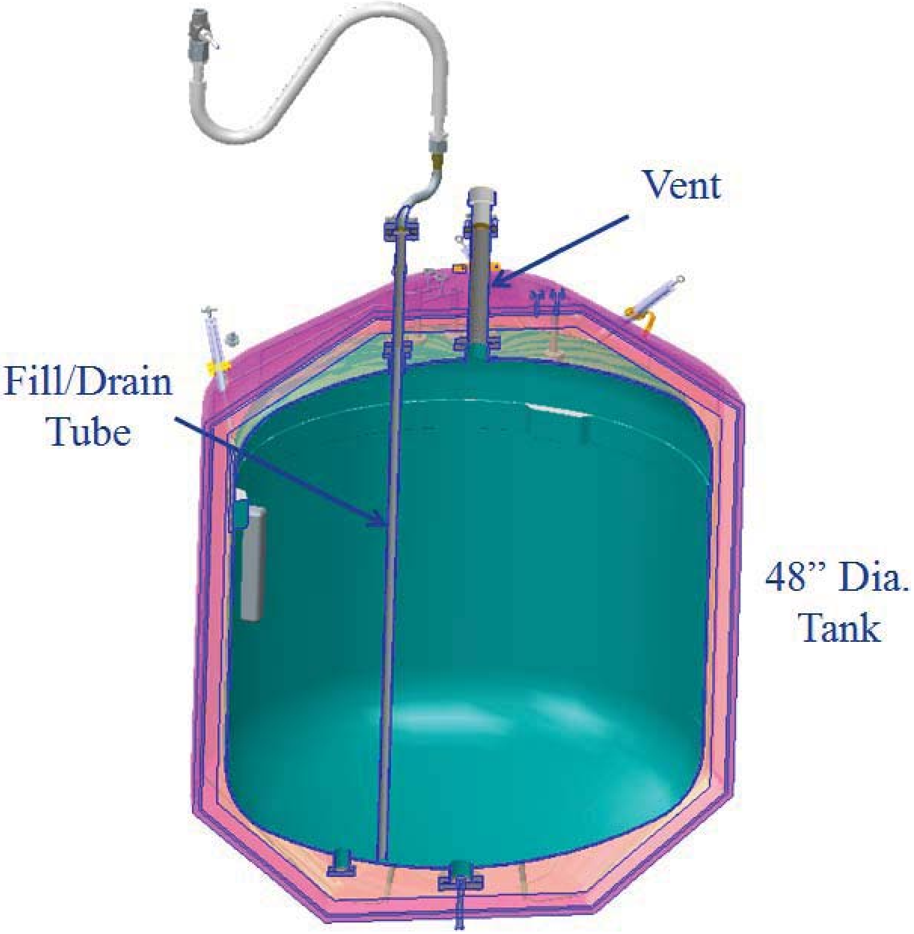
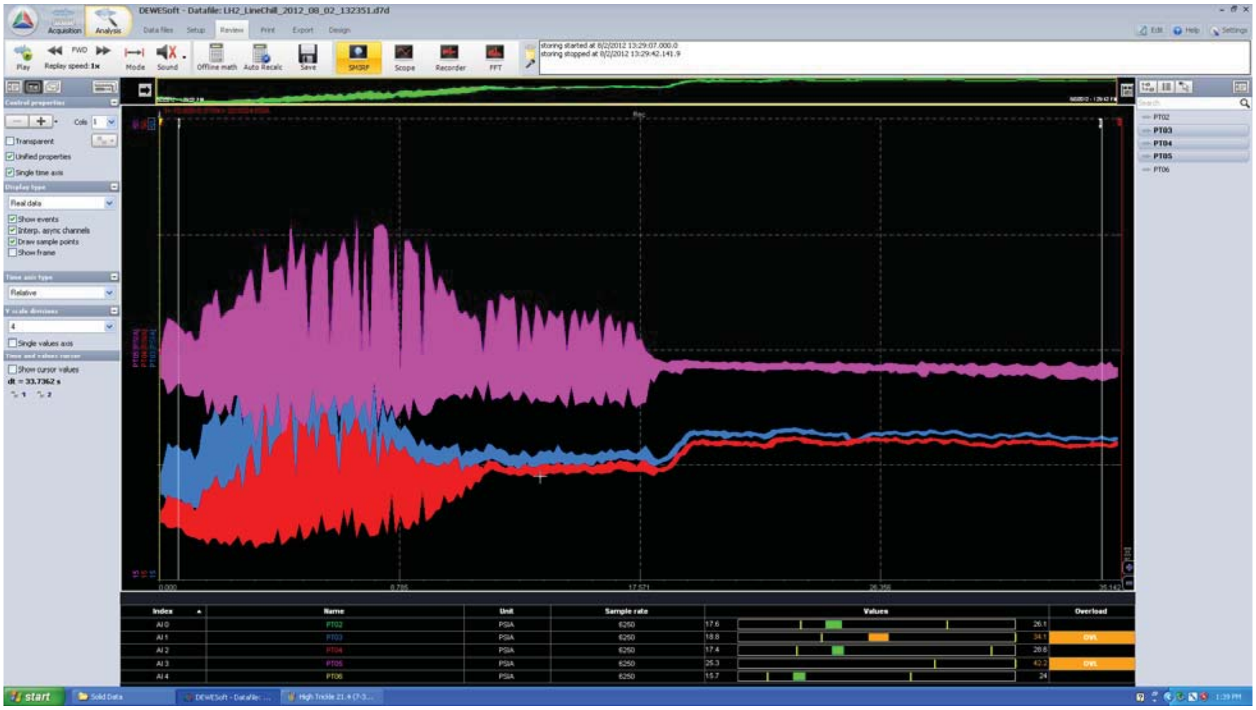


Figure 3, Cryogenic Boil-Off Reduction System Test Tank.

The pressure transducer did reveal that oscillations were occurring. The low frequency component was measured to have a frequency of 15Hz. After a period, the cross-over valve was opened and the TAOs immediately dissipated, as can be seen in Figure 4.



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Index	Name	Unit	Sample rate	Values		Overload
AI 0	PT02	PSIA	6250	17.6	26.1	
AI 1	PT03	PSIA	6250	18.8	34.1	OVL
AI 2	PT04	PSIA	6250	17.4	28.6	
AI 3	PT05	PSIA	6250	25.3	42.2	OVL
AI 4	PT06	PSIA	6250	15.7	24	

Figure 4, Pressure Transducer Output Display Showing Existence and Elimination of the TAOs.

When TAO is occurring and liquid is not in the tube, the tube acts as a ¼ wavelength tube as shown in Figure 5, and the lowest resonant frequency can be calculated:

$f = c / \lambda$
λ: wavelength, i.e. 4 x tube length
c: speed of sound at vapor temperature

At 20K the resonant frequency for hydrogen vapor in a 1 meter long tube would be $85s^{-1}$.

Figure 5, Quarter Wavelength Tube.

STUDIES

Gu & Timmerhaus at the University of Colorado have done many studies and experiments related to TAO in cryogenic systems. They developed a model for determining whether a half-tube was stable or not, as a function of tube inner radius, hot-end to cold-end temperature-ratio (α), and hot-end to cold-end length-ratio (ξ). His model is for a 1 meter long tube with a step change in temperature, but he has also examined the effect of different temperature ratios. The physical model of what he studied is shown in Figure 6.

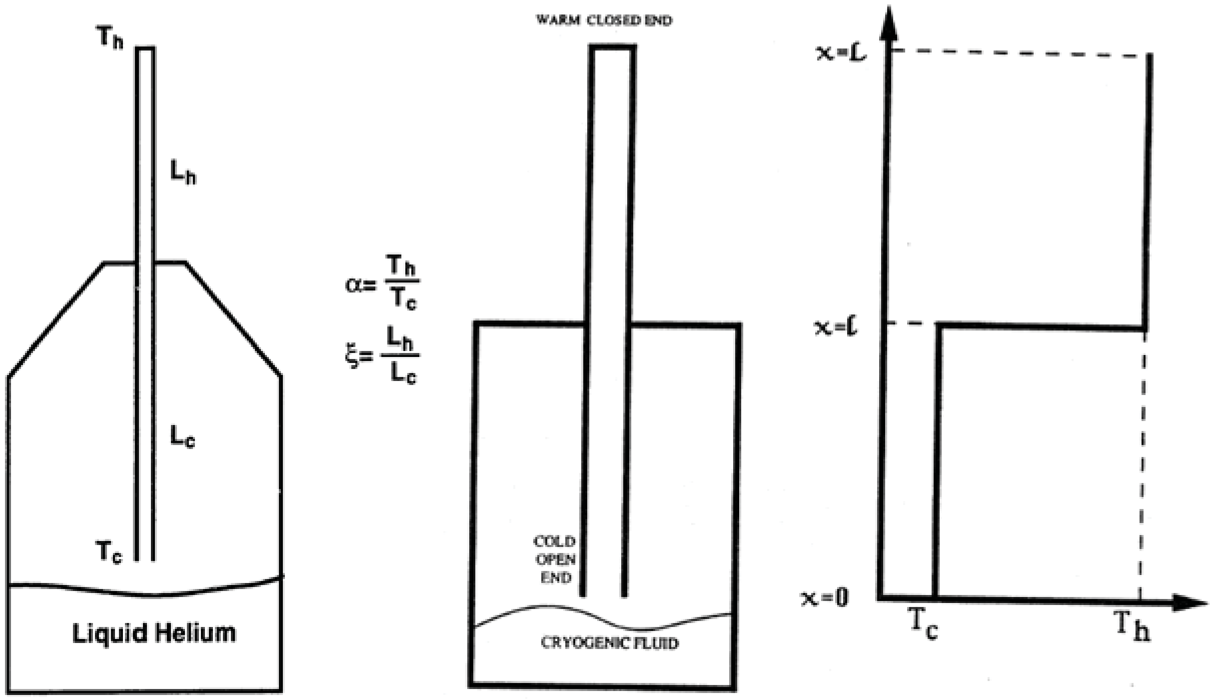


Figure 6, Schematic of the Thermal Acoustic Oscillation System [2].

The results from one model are shown in Figure 7. This model is a 1 meter long tube filled with hydrogen vapor. The cold end is at the normal boiling point and there is a step change in temperature between the warm tube and the cold tube. The vertical axis is the temperature ratio (α) of the T_{hot} divided by T_{cold}. The various curves are for different length ratios (ξ) of L_{hot} divided by L_{cold} and this plot is for length ratios greater than 1. Much insight can be gleaned by examining the behaviors of these curves.

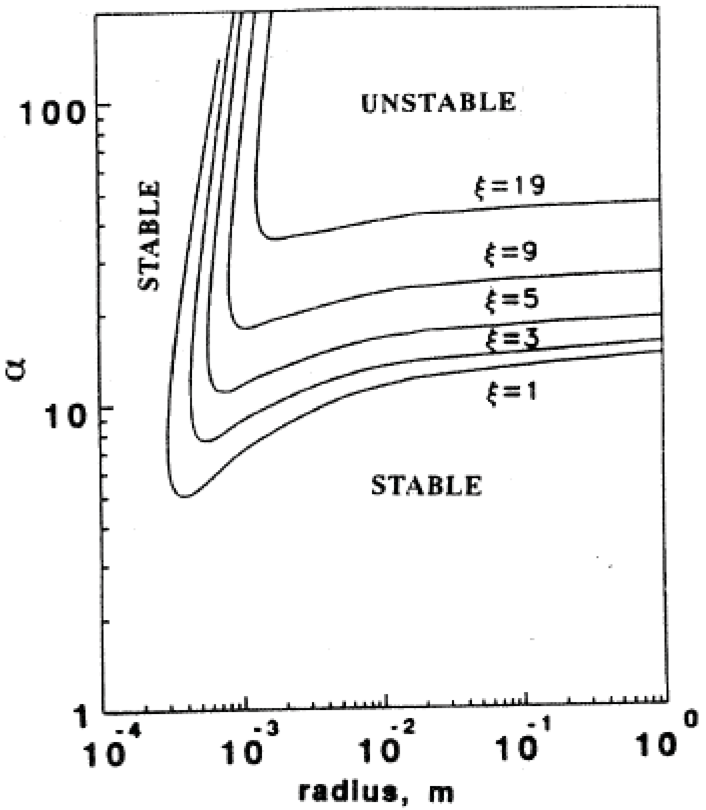


Figure 7, Critical Radii for Thermal Acoustic Oscillations in a Normal Boiling Point Parahydrogen System with a 1 Meter Long Tube, a Step Change in Temperature and Length Ratios Greater Than 1 [3].

Gu & Timmerhaus intended for these curves to be used to find the critical radius, but in practical application tube radii are fixed or the designer is limited to very few choices. In Figure 8, typical tube sizes are shown, along with a typical temperature ratio of 300K/20K = 15. As an example consider a ¼" tube with a length ratio of ξ=6. The plot shows if the length ratio is greater than approximately 5, that the system is unstable. It could be made stable by increasing or decreasing the tube size. Decreasing the tube diameter is probably not practical because the tube inner diameter would only be 0.024", but this might be acceptable for a pressure transducer. If we increase the tube diameter it would need to increase to 1". The curves are very shallow to the right, therefore large increases in tube diameter are required. The system could be made stable by increasing the length ratio. If the length of the warm tube was increased to achieve a ratio of ξ=9, the system would be stable. The system could also be made stable by decreasing the temperature ratio. If the warm end temperature was lowered to achieve a temperature ratio of α=11, the system would become stable.

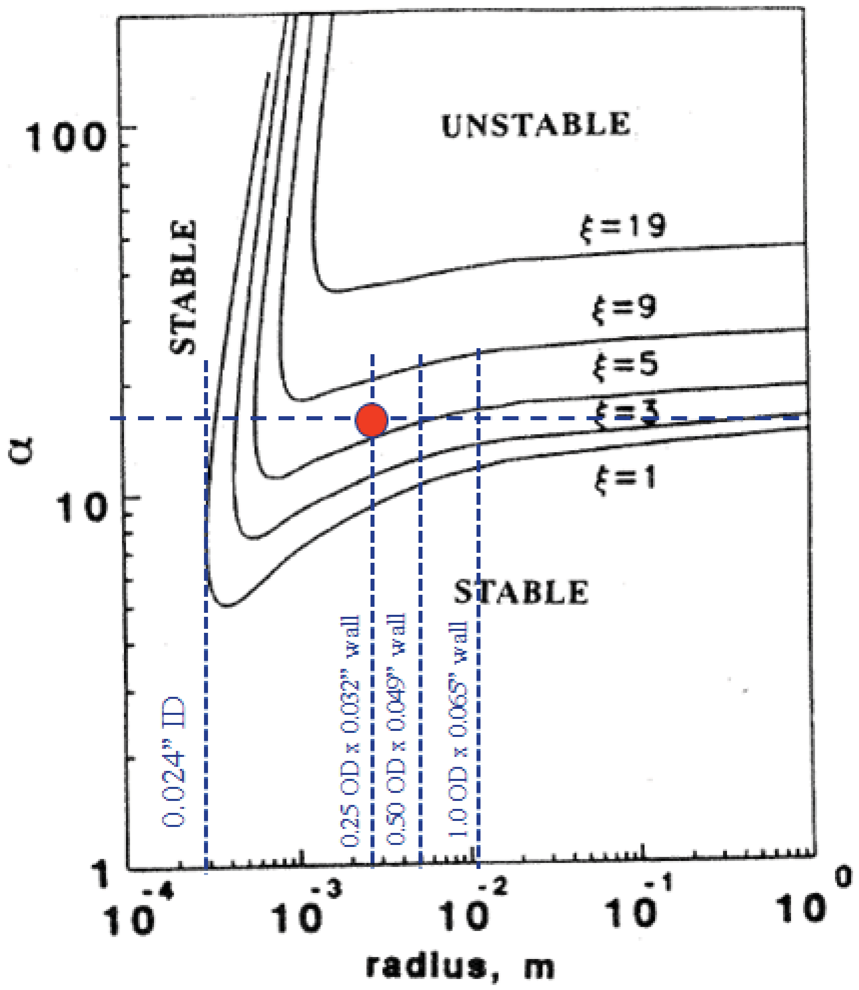


Figure 8, Stability Plot using Typical Tube Sizes [3].

Gu's analyses have also shown that the lowest unstable temperature ratios occur for length ratios equal to 1. Figure 9 shows the stability plot for length ratios less than 1 and shows that when the cold tube length becomes greater than the warm tube length it has the same effect as the other way around. The examples he discusses can be found in reference [4]. His analyses also showed that above is true when the tube ends above the liquid, but if tube end is submersed and liquid enters the tube a different feature occurs, see Figure 10. The addition of liquid mass into the tube greatly reduces the stable regions of the plot, and reducing the length ratio below 1 has little effect.

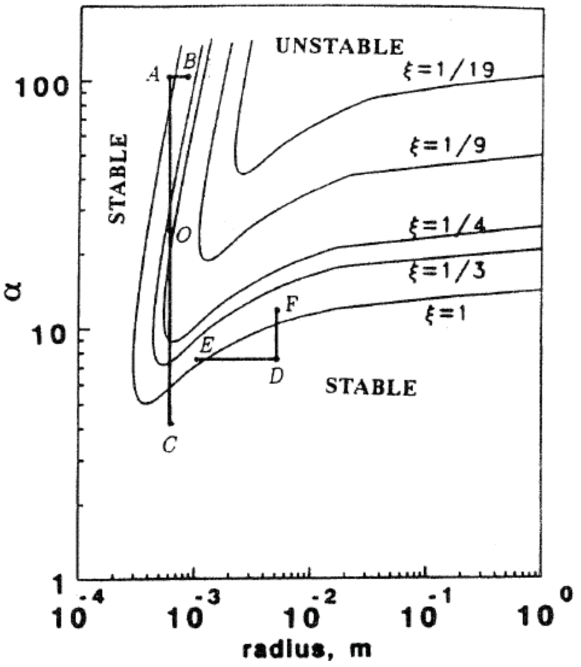


Figure 9, Stability Plot for Length Ratios < 1 [4].

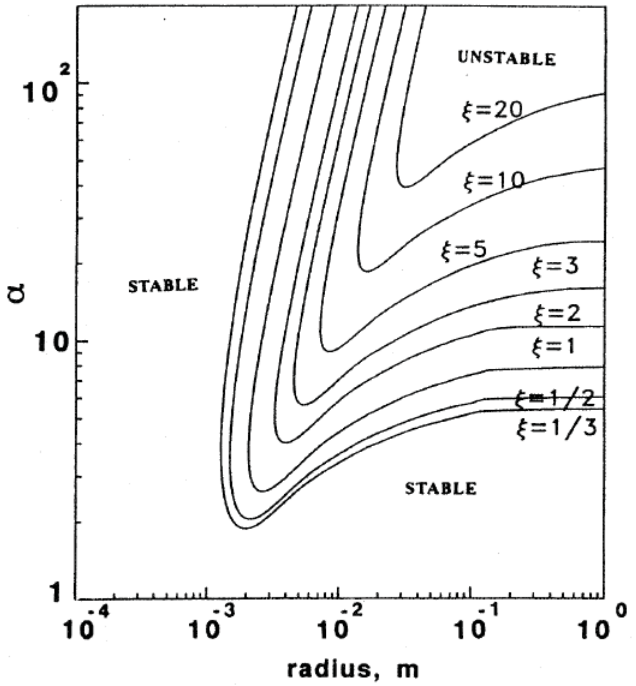


Figure 10, Stability Plot When Open End of the Tube is Located below the Surface [4].

Experiments performed at the Institute for High Energy Physics in Russia showed how the resonant frequency of a TAO system changed as the tube end approach the liquid surface and as it became submersed [5]. As shown in Figure 11, an abrupt change in frequency did not occur until the tube end was submerged over 20cm. This indicates that fluid is not entering the tube until there is significant pressure head height. Note that the He case had oscillation when the tube was above the surface.

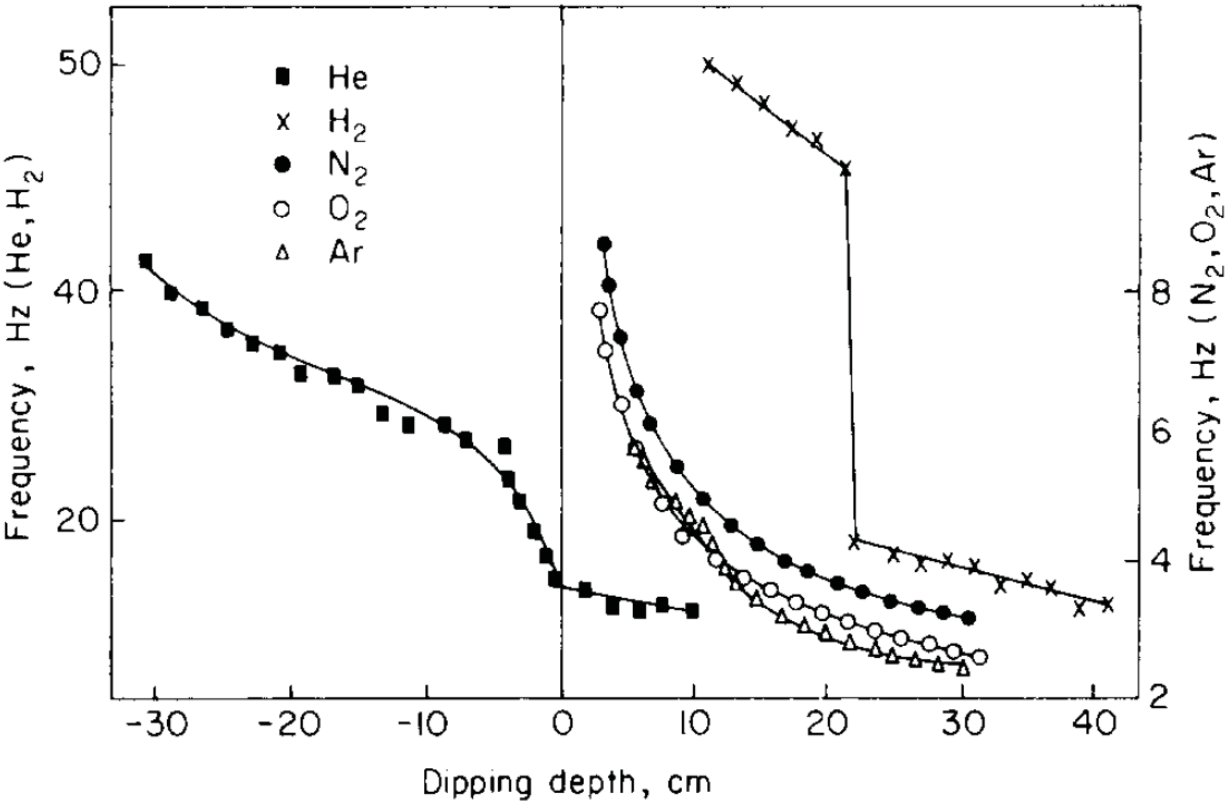


Figure 11, Frequency Characteristics of Oscillation vs. Dipping Depth [5].

PREVENTION

To prevent TAO, it is important to first understand the forces involved. There are three forces at work: the driving force, the viscous resistance and the inertial force. The driving force is the temperature ratio and the heat transfer area. The driving force is directly proportional to the warm end tube length and the viscous resistance is predominated by the warm section, when the length ratio is greater 1. As shown in Figure 8 through Figure 10, knowledge of length ratio is critical in determining the stability solution.

The inertial force is provided by the oscillating mass which is a function of the pressure, temperature, and volume of gas in the cold section. This mass rapidly increases when liquid enters the tube.

There are many ways to prevent TAO from occurring. A very effective method is to reduce the temperature ratio below the critical value, i.e. make the warm end colder. This can typically be done by insulating the warm end of the tube.

In most practical situations the system state point will be in the right hand portion of the stability plot. In this region stability can be achieved by increasing the length ratio, i.e. increase the length of the warm section and/or decreasing the length of the cold section. The warm gas is more viscous and increasing is length increases the viscous damping. Shorting the cold section reduces the mass of the high density slug, thus increasing the influence of warm end damping. Stability can be achieved by increasing or decreasing length ratio: for example, in Figure 9, going from point O to A or from point O to C.

Viscous damping can be increased by reducing tube radius, as done in Figure 9 when going from point B to A. Inertial damping can be increased by increasing tube diameter as was done when going from point E to D. Since the cold end has little viscous damping, adding a restriction to the cold end will provide that end some resistance to flow. "Increasing the restriction of the cold end is very effective in preventing TAOs" [4]. So consider adding an orifice or a filter to the cold end.

When liquid enters the tube, the frequency is lowered and TAO is more easily excited. In a typical cryogenic dewar system when liquid enters the tube, it will boil and the vapor will force some of the remaining liquid out. In some cases a heat-pipe phenomena can occur; and liquid can wick-up the tube wall and then boil in the warmer region of the tube. Both of these phenomena make determining the liquid level in the tube difficult to predict.

Changing the temperature gradient is also very effective. Gu & Timmerhaus studied various temperature gradient profiles ranging from a step profile to a linear gradient as shown in Figure 12. As can be seen in Figure 13, the critical temperature ratio rises significantly as the gradient become more linear. For a triple point parahydrogen system with a tube length of 1m and a length ratio of 1, if the temperature ratio is 300/20=15, the system will be stable for any diameter tube with a linear thermal gradient. The summary of mitigation methods is shown in Figure 14.

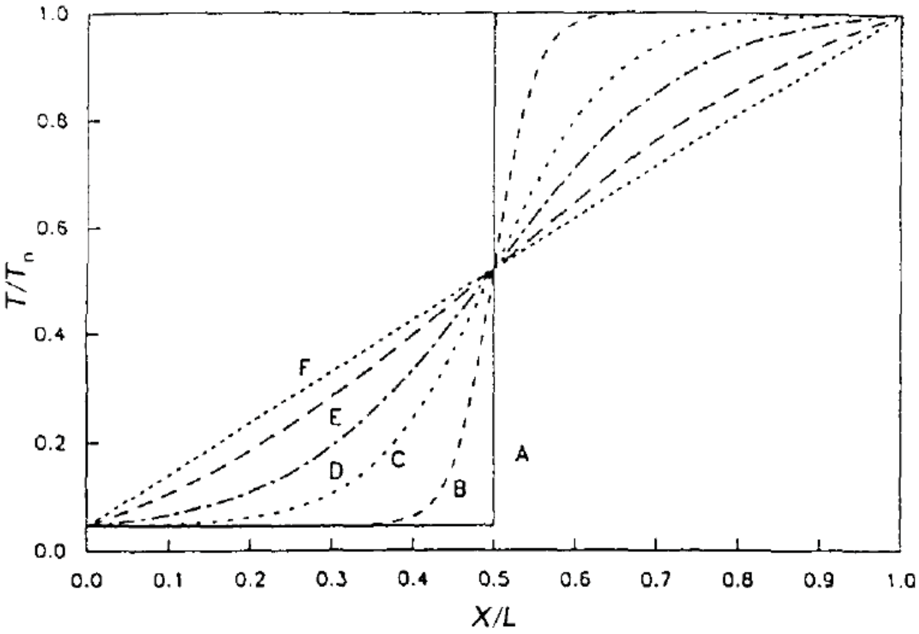


Figure 12, Different Temperature Profiles Investigated [7].

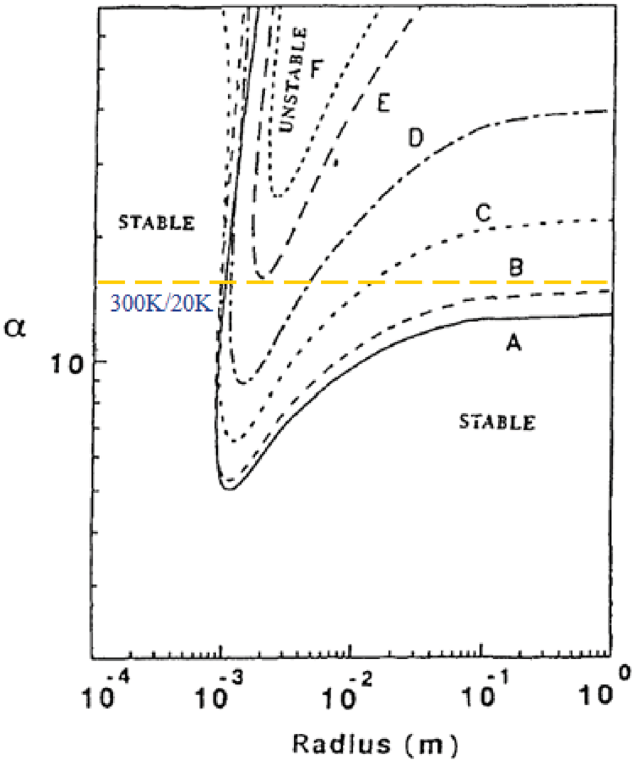
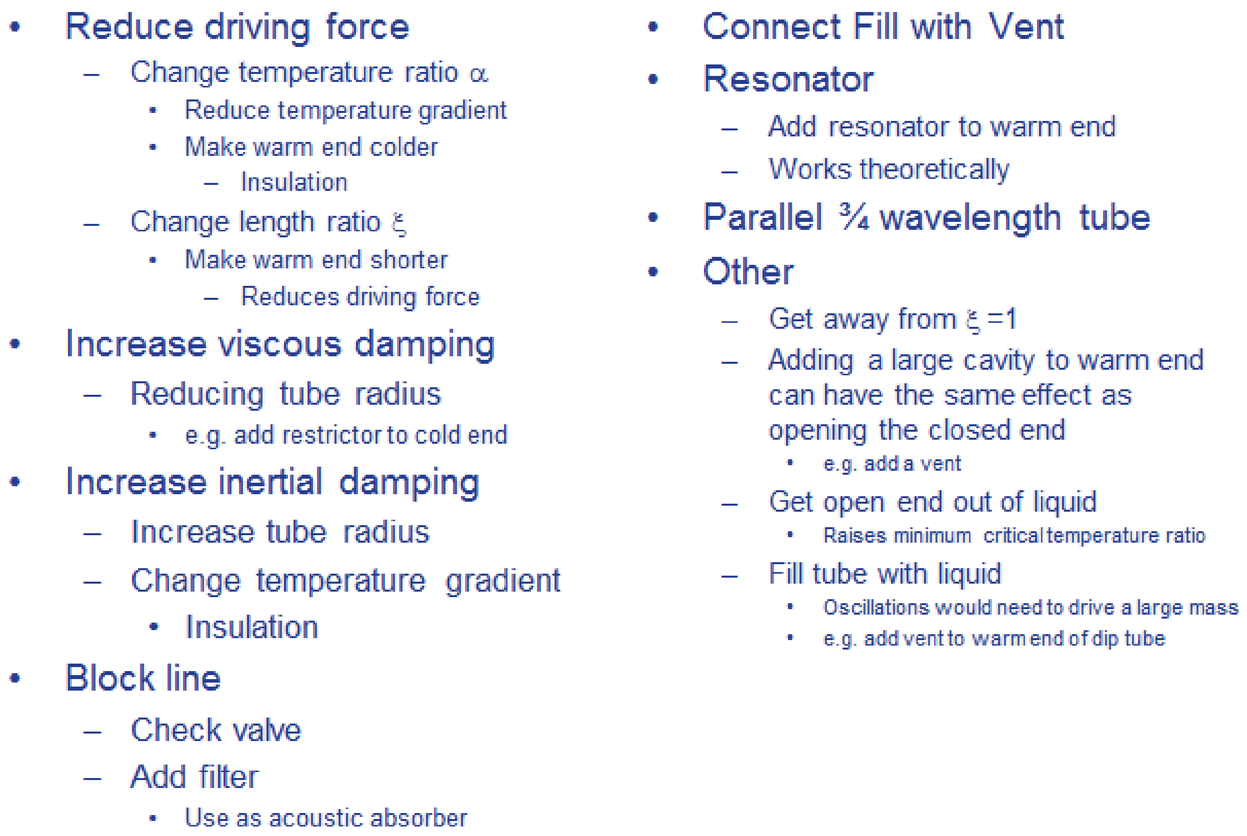


Figure 13, Critical Temperature Ratio
for Various Temperature Gradients
L = 1, ξ=1. Triple-point parahydrogen [7].



- Reduce driving force
  - Change temperature ratio α
    - Reduce temperature gradient
    - Make warm end colder
      - Insulation
  - Change length ratio ξ
    - 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 ¾ wavelength tube
- Other
  - Get away from ξ =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

Figure 14, Summary of Mitigation Methods.

ANALYSIS

For a given fluid, assumed temperature profile in the line, hot to cold boundary temperature ratio, hot to cold line length ratio, and length of line, models from Gu and Timmerhaus and Figure 12 and Figure 13 can be applied to determine the frequency of oscillation as well as the cirtical radius of the line to initiate TAOs. As an example, the models are applied to the following system to determine the critical radius and TAO frequency:

1. Para-hydrogen
2. Assumed step profile in the line (Curve A from Figure 12)
3. Hot boundary temperature is 300K, cold boundary temperature is 20K; $\alpha = 15$
4. Length of line is 1 meter.

From Figure 13, for a given ξ, all radii to the left and below the curve are unstable points where TAOs will occur; for all points to the right and above the stability curve, TAOs will not occur. Table 1 shows the critical radius for different assumed hot to cold length ratios.

Table 1 – Stability Conditions for Mitigating TAOs in a 1 Meter Tube in LH_2, $\alpha = 15$

	critical r @ L = 1m [in]
ξ = 1	< 0.4
ξ = 3	r < 0.58
ξ = 5	r > 2
ξ = 7.5	Stable

Models indicate that the frequency of oscillation is also highly dependent on the assumed hot to cold length ratio. Over the range of assumed ξ from Table 1, the range of frequencies is 110Hz – 185 Hz. Similar methods can be applied for tubes greater or less in length than 1 meter. Employing any of the mitigation methods from Figure 14 would allow a more stable solution for a larger diameter or longer length tube.

CONCLUSIONS

Thermal acoustic oscillation can easily occur in cryogenic systems, producing unwanted heat and boil-off loss of cryogens. These acoustic oscillations can be predicted and simple changes in design can eliminate these oscillations.

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