Thermal Acoustic Oscillations: Short Review and Countermeasures

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Abstract. Thermally driven oscillations in capillaries of helium cryogenic systems could be observed when a local heat source occurs or a continuous cold to warm temperature transition along capillary exists. These oscillations could lead to a significant heat flux as well as for pressure disturbances. Therefore, it is practically important to design cryogenic systems robust against possible disturbances due to Thermal Acoustic Oscillations (TAO). In the present paper, a short review on available theoretical and experimental results related to the TAO is given. Some tips for a design as well as in-situ countermeasures are discussed.

1. Introduction
Thermal Acoustic Oscillations (TAO) could occur in cryogenic systems, when a tube, which is opened at cold state and closed at warm one with sufficiently large ratios of warm to cold temperatures as well as length to radius, exists. Typical examples are capillaries used either for pressure gauges or for wires of temperature transmitters, as well as slots between rotating parts of a turbo-machinery [1-2]. Other examples could be local heating points (also called “hot spots”). Such oscillations could lead to the significant heat loads of range 1-250W or pressure oscillations up to 0.5 bar(g), which is not tolerable for accelerators with superconducting cavities [13]. Therefore, avoiding TAO is of paramount importance for the cryogenic systems with limited cryogenic capacities as well as for cryostats with the superconducting cavities [1-29, 37-58].

In the first part of this paper, a short literature review on the TAO is given. In the second part, some design criteria for a construction of the cryogenic systems, which are robust against the TAO, are presented. In the next part, some tips related to the countermeasures against existing TAOs are summarized.

2. Literature review

2.1 Usual TAO (also called “typical”)
TAO could occur in the cryogenic systems, if a tube, which is closed at the warm end and opened at cold one, is placed between warm and cold regions, so large temperature gradient exists along the length of the tube. Due to a small disturbance, gas inside the tube will move between warm and cold parts periodically exchanging a heat between warm and cold regions. Theoretical background of TAO for the helium was successfully developed by Nikolaus Rott [3-8] and for practical applications it is
often reasonable to design the cryogenic systems according to a stability diagram, see Figure 1, where unstable region with possible oscillations is located between two curves. Stability at left-hand side is limited to the diameter of the tube at the warm side: Stockes boundary layer is large and fills the whole capillary, which prohibits oscillation of the gaseous helium (GHe), which could transfer energy from warm to cold parts. Stability at the right-hand side is limited to the diameter of the tube at warm and cold parts: Stockes boundary layer is small at warm and cold parts, so there is a lack of a sufficient cooling and heating from the tubes to GHe.

Typical parameters, which influence a shape of the stability curve, are: a) gas art, b) opened end of tube in liquid or gas phase, c) smooth or sharp temperature transition along the capillary, d) ratio of warm to cold lengths of capillary, e) variation of a capillary cross-sectional area, f) ratio of warm to cold temperatures. The TAO could be initiated by [12]: a) amount of cryogenic fluid in vessel, b) absolute pressure, c) moving the tube close to the liquid and then withdrawing it. Intensity of the TAO also depends on a heat flow along the tube, e.g. whether it is constructed from aluminum or steel. It is also worth to note that for large tubes with diameters ca. 10 mm or above, it is easier to get anomalous TAO, see next chapter.

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**Figure 1.** Thermal Acoustic Oscillations [9], where \( T_w \): Temperature warm part, \( T_k \): Temperature cold part, \( d \): Diameter of capillary, \( c \): Velocity of sound cold, \( \ell \): length cold, \( \zeta \): Ratio length warm / length cold, \( \nu \): kinematic viscosity at cold temperature. The ordinate axis represents temperature ratio, the abscissa axis – dimensional parameter, and \( \zeta \) is parameter describing warm to cold end ratio of capillaries or tubes.

**Figure 2.** Waveforms for: (a) usual thermoacoustic oscillations, (b) resonance (anomalous) oscillations, (c) unsteady resonance oscillations [10, 11].

### 2.2 Anomalous TAO (also called “high intensity” or “resonance”)

The anomalous TAO occurs in tubes with one end located inside the liquid helium (LHe), which leads to an evaporation and condensation of LHe inside this tube with subsequent energy transfer from warm to cold part. Due to a very low latent heat of LHe, liquid is easily evaporated, which leads a large pressure increase and non-linear oscillations, see Figures 2, 3. The process begins with a drawing LHe into tube as with ordinary TAO, but continues more intensive, because there is a gas expansion at the warm end that acts as a weakened spring. The presence of a vacuum insulation around tube helps to preserve the wall heat of the previous cycle, which is necessary for LHe superheating. Having achieved a maximum velocity, LHe boils up, pressure in the tube grows and the resulting vapor-liquid mixture is pushed out of the tube in both directions. At the outlet of the warm tube part, most of the liquid is evaporated and vapor is warmed up due to the heat of the walls, see Figure 3. Typical heat load is in the range of 10-250 W. For an occurrence of the anomalous TAO, the following conditions must be met [10]:

a) The flow area of the warm portion exceeds the flow area of the cold one by no less than 2-2.5.
b) Lateral surface of tube (cold section) is well heat insulated, e.g. by vacuum.
c) The tube end, immersed into LHe, is placed no less than 30-40mm from the vessel bottom.
d) The transition to the warm portion is smooth, without bends, and the tube has no restrictions (including wires) in the cold ones.

![Figure 3. Anomalous (high intensity) TAO [10, 11]. Pressure in capillary is given in the left scale, while pressure in dewar – in right one.](image)

It is also worth to mention that the TAO could occur also in vessels with other cryogenic gasses, see Figure 4.

3. Design considerations for TAO reduction
In this chapter, some practical design tips that can help to avoid TAO are given.

3.1 Taking the tube away from the LHe surface for avoiding boiling off / stirring of LHe
This is a standard solution for the small cryostats. Typically, two lines are installed; one for the LHe filling to the bottom of the cryostat and one for the top filling, though sometimes one line with disconnectable joint is also used. Two solutions are possible, either to remove LHe filling line after helium transfer, or to disconnect the upper part from lower one and move it away from LHe. For the case, if such LHe transfer line with one end in LHe is permanently installed, a connection to the warm recovery line in order to have a small GHe flow could be very helpful.

3.2 Avoiding “closed line”, e.g. by connecting them with some other opened lines, e.g. fill and vent lines or to cryostat GHe volume
The main idea is to connect warm GHe, which is closed inside the line, to the warm GHe at the cryostat. So, volumes with warm GHe (inside the pipe and in cryostat) are connected, which leads to reduction of warm GHe flow and avoidance of the TAO. This is simple and efficient solution. It is also often helps to localize the pipe with TAO. This method is quite easy to implement to small will medium cryostats, because there are typically plenty of flanges free for connections; but it is quite challenging for industrial helium facilities, because helium reservoirs are typically closed by insulation vacuum from all sides, and, therefore, connection to warm GHe volume could be not available.

3.3 Enlargement of cross-sectional area at cold and reduction at warm ends
This is reasonably simple solution, if free space inside the cryomodule or cryostat is available.

3.4 Thermal insulation of the tube at low temperatures, i.e. steady temperature gradients, no steps
The steps in temperature gradients must be avoided. Thermal insulation with superinsulation of single capillaries or very small tubes is quite unpractical, and avoiding the thermal anchoring at 40-80K temperature level is already sufficient in order to obtain smooth temperature gradient along the tube.

The case of thermal anchoring of capillaries at some intermediate temperature of around 80K needs some more discussion. In case of no thermal anchoring, the temperature transition along the capillary
is smooth, which leads to reduction of TAO probability. Moreover, due to non-linear thermal conductivity of stainless steels, the “averaged” temperature of 150K is not located at the middle of the capillary, and, therefore, the ratio of warm to cold capillary lengths is not 1, which also leads to reduction of TAO. In case of thermal anchoring installation, which is typically installed closed to warm capillary end, two competitive effects occur, i.e. enhancement of TAO due to sharp temperature transition between 300 and 80K, and reduction of TAO due to changed ratio of warm to cold capillary lengths. It is often very difficult to predict or estimate, which of these two effects prevails, so according to the author’s experience, it would be better to avoid thermal anchoring for cold capillaries or tubes.

3.5 Low pressure check valve
This solution is quite controversial. The main reason is that the check valve could also oscillate and these oscillations are quite difficult to distinguish from TAO. Two solutions are existing, classical spring-loaded version and clapper valve, the letter must be installed in the vertical direction. Both versions are typically large for the installation on 6 mm tubes. Unfortunately, systematic measurements or a long-term experience with the check valves for avoiding of the TAO are missing, and only limited experimental data are available on the oscillations of check-valve for pipes with large diameters. It would be very helpful to have more data published in the open literature. A general tendency at many cryogenic laboratories is to avoid check-valves at helium temperatures and only to install them only when it is absolutely necessary.

3.6 Buffer volumes with restriction element, e.g. capillary, porous body, valve, orifice
The main idea is to have a “relative large” volume, so the pressure inside is approximately constant, and some restriction element. In this case, the oscillations, produced by this buffer volume with the restriction element are in opposite phase than ones of TAO, so a damping occurs. It is worth to mention that it is not possible to avoid oscillations, but it could be possible to achieve a sufficient damping.

Buffer volume at low temperature:
This solution is rarely used for damping of TAO, but relatively often for avoiding of density-valve oscillations, or ones produced by moving parts of a cold machinery.

Buffer volume at room temperature:
Damping factor related to the intensity (power) is [29]:

\[ \pi = \frac{\left( \frac{\rho c}{2S} \right)^2 + \frac{\rho c^2}{\omega} \left( \frac{L}{a} \right)}{\left( \frac{\rho c}{2S} \right)^2 + \frac{\rho c^2}{\omega} \left( \frac{L}{a} \right)} \]

and required conditions:

\[ \frac{\rho c}{2S} = \frac{8\mu L}{\pi a^4} \left( \frac{4\rho \omega V}{\pi a^2} - \frac{\rho c^2}{\omega V} \right) \leq \frac{\rho c}{S} \]

where \( \rho \) is a density of GHe at low temperature, \( S \) is a cross-sectional area of a helium process tube, \( c \) is a sound velocity in helium at low temperature, \( R_0 \) is real part of damping impedance, \( \omega \) is angular frequency of wave, \( a \) is capillary radius, \( L \) is capillary length, \( V \) is volume of the surge tank, and \( \mu \) is viscosity of helium at low temperatures.

It is also possible to use a sinter metal tube closed by other volume, e.g. tube [42]; though it is less practical due to danger of sinter blocking due to for example dust, and modification of tube due to cutting and welding activities.

It is worth particular to strength that application of the buffer volume but without restriction element, for example capillary or valve, could lead to an opposite effect, i.e. oscillation intensities are increased [31].

3.7 Increasing of warm pipe length at 300K
By changing a ratio between warm and cold parts of the capillary, it is possible to decrease the unstable region, see Figure 1.

The formula derived from experiments on 6*1 mm capillary is given as [25]:

\[ L_{\text{warm}} \geq 693 \cdot d^{0.75} \cdot L_{\text{cold}}^{-0.2} \]

where \( L_{\text{warm}} \) (m) and \( L_{\text{cold}} \) (m) are total lengths of tube at
temperatures above 150 and below 150K, respectively, \(d\) (m) is an inner diameter of the capillary.

It is worth to note that for practical implementations quite long capillaries must be installed. For example, for cold capillary of 1 m length and 4 mm inside diameter, the minimal length of a warm part is around 11 m.

### 3.8 Insertion of wires into warm end of tube

For the case if a free cross-sectional area is free from obstacles, it is possible to insert a wire into the capillary.

Damping factor related to the intensity (power) is [21, 29, 42]:

\[
\pi = \frac{(r_b^2 - \frac{r_c^2}{2})^2 + x_b^2}{(r_b^2 + \frac{r_c^2}{2})^2 + x_b^2}, \quad R_b = \frac{\frac{\pi \mu L}{r_b} \frac{\frac{\rho c}{2}}{r_b}}{(r_b^2 + \frac{r_c^2}{2})^2 + x_b^2} = \frac{\frac{\pi \mu L}{r_b} \frac{\frac{\rho c}{2}}{r_b}}{(r_b^2 + \frac{r_c^2}{2})^2 + x_b^2}, \quad X_b = \frac{4}{3} \frac{\rho c}{r_b} \frac{\frac{\pi \mu L}{r_b} \frac{\frac{\rho c}{2}}{r_b}}{(r_b^2 + \frac{r_c^2}{2})^2 + x_b^2}, \quad \text{required conditions:} \quad \left. \begin{array}{l}
\frac{\rho c}{2} = \frac{\pi \mu L}{r_b} \frac{\frac{\rho c}{2}}{r_b} \\
\frac{4}{3} \frac{\rho c}{r_b} \frac{\frac{\pi \mu L}{r_b} \frac{\frac{\rho c}{2}}{r_b}}{\pi (r_b^2 + \frac{r_c^2}{2})} \leq \frac{\rho c}{S}
\end{array} \right\}
\]

\(r_2\) is an inside diameter of the capillary or small tube and \(r_1\) is an outside diameter of wire.

It is worth to pay special attention to the case of reduction of free cross-sectional area inside the cold capillaries or tubes. On one hand, due to sharp bendings of capillaries some reduction of cross-sectional area occurs, which leads to enhancement of TAO. On the other hand, due to significant cross-sectional area reduction, e.g. due to cold capillary squeezing or installation of glass wool inside or some sinter material, significant gas flow reduction is achieved, which leads to reduction of TAO probability. According to the author personal preference, it is better to avoid cold capillary squeezing (capillary will be “useless” after that and no pressure measurements will be possible), and to avoid any glass wool installation inside small capillaries because during pump & purge activities, some gas flow or pressure waves shock could occur, which could lead to glass wool movement or propagation inside the cryogenic system.

### 3.9 (small) He gas flow through the capillary

In many cases, this method brings positive results, i.e. TAO are absent or sufficiently reduced. It is possible to release the GHe into the atmosphere, if no recovery line is available. For practical implementations, in many cases a throttling valve is sufficient; though in some cases a flow meter is additionally installed for the reason to have a required flow rate, and, therefore, a control loop valve-flow meter is installed. It is worth also to mention that for very high GHe flow rates an additional control loop with heater and temperature sensor is required in order to avoid icing of the tube or capillary.

### 3.10 Heat sinking/warming for the closed lines

For the case, if oscillations are observed to be close to the left side of stability curve, see Figure 1, it is possible to warm up the warm part of the capillary. In this case the measured point is moved up and possibly gets the stable conditions. Though this method seems simple, it has practical drawbacks, i.e. i) oscillations should be close to the transition region, ii) heating is not always possible, iii) effect is very limited, e.g. by warming from 20 to 50 °C, the temperature ratio is increased by \((273+50)/4.2=77\) in comparison to ambient temperature, \((273+20)/4.2=70\).

Similar considerations are applicable to the right side of the stability curve. In this case, cooling of a warm part of the capillary is necessary.

### 3.11 Venting holes in the middle of tube

In this case the ratio of warm to cold tube is changed and stability region is increased, see also chapter 3.7. It is quite difficult to apply this method, because for the permanently installed capillary or tube it is not possible to have holes due to leakages into an insulation vacuum, and for the temporary installed tubes, it is necessary to change it, i.e. for LHe transfer – tube without holes, for the stand-by – tube with holes.

Figures 5 and 6 are summarizing the design examples of capillaries or small tubes, which lead to enhancement and reduction of TAO.
Avoiding an increasing of the cross-sectional area inside the cryostats, i.e. in the temperature transition from 4.2 to 300 K.

Avoiding an increasing of the cross-sectional area outside the cryostats, i.e. in transition from 4.2 to 300 K level.

Avoiding (when possible) the lines, tubes or capillaries, e.g. fill lines, left in the LHe.

Avoiding (when possible) the closed lines, tubes, or capillaries at 300 K.

Avoiding the reduction of cross-sectional area inside the cryostats, i.e. in temperature transition between 300 and 4.2 K, e.g. due to (unintentional) sharp bendings.

Avoiding the thermal anchoring at 40-80 K temperature levels, i.e. increasing of a sharpness of the temperature transition. Keep smooth temperature transition.

Installation of a valve connecting the closed lines, tubes, or capillary to the GHe recovery line (TAO are typically suppressed by gas flow).

Figure 5. Some typical design examples (“DON’T”), which could lead to enhancement of TAO

Keep the same the cross-sectional area inside the cryostats, i.e. in transition between 300 and 4.2 K levels.

Decrease (if possible) the cross-sectional area outside the cryostats, i.e. at 300 K temperature level.

Making lines or tubes movable (whenever possible), e.g. fill lines.

Increase (if possible) the cross-sectional area inside the cryostats at 4.2 K level.

Figure 6. Some typical design examples (“DO”), which lead to reduction of TAO

4. In-situ measurements and countermeasures

The first “detection” of TAO is typically performed by a visual inspection, e.g. by observing an ice block around the capillary. Connection of a small and fast pressure transmitter for Fast Fourier Transformation over the purge connection of the capillary is necessary for the measurements of spectral intensities of TAO inside the capillary.

It is worth to note, that the purge connections, which could be used for an installation of the pressure transmitters, are typical for cryogenic systems operating above the atmospheric pressure; but in some cases they are avoided for cryogenic systems operating at sub-atmospheric pressures due to
possible air leakages. In some cases, additional connections with flanges for volumes between spindle and valve body or between tubes in Johnston couplings could be also used for the pressure measurements, though due to a small gap between tubes, a significant damping of pressure oscillations could occur.

The most critical point is an interpretation of results, because in addition to TAO, there could be several other sources of pressure oscillations, e.g. rotating machinery, check-valves, and density-wave oscillations [59]. So, switching on/off of rotating machinery, variation of mass flow will influence the operation of check-valves, rotating machinery or density-wave oscillations [30-36] and it could be possible to identify the sources, which could initiate the TAO inside the capillary or small tubes.

In case if the source, which initiates the TAO is not found, it is possible to apply some practical recipes, which are summarized in Figure 7.

Figure 7. Some typical recipes used for the reduction of the TAO.

From the author’s practical experience, the first choice would be the buffer vessel with the needle valve and integrated pressure transmitter, see also reference [13] for one of possible examples. It has several advantages; i) it is possible to prepare such set-ups in advance, for example for 6*1 and 4*0.5 mm capillaries, or with different sizes of buffer vessels and needle valves, ii) adjusting of flow impedences by the needle/micrometre valve allows the TAO suppression in wide frequency ranges as well as in amplitudes. If this solution leads to not sufficient damping, the next choice would be GHe flow (it should be noted that in this case, GHe flow is relative “high”).

5. Conclusion
In the present paper, a short literature review on the TAO is presented.

Designs of capillaries or small tubes, which could lead to reduction or damping of TAO, are considered.

In-situ measurements and countermeasures of TAO are also shortly discussed.

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