

Occurrence of Thermoacoustic Phenomena at 0.8 K, 4 K and above

W. Stautner¹, R. Chen², M. Xu¹, J. Rochford¹, J. Trigger¹

¹Electromagnetics & Superconductivity Lab, GE Global Research, Niskayuna, NY, 12309 USA

²Chemical Sensing Lab, GE Global Research, Niskayuna, NY, 12309 USA

E-mail: stautner@ge.com

Abstract. Thermoacoustics in cryogenics continues to be a very interesting phenomenon which is still poorly understood but often experienced unexpectedly in experiments where it causes unacceptable heat leaks. The authors report on the appearance and onset of this unwanted occurrence at temperatures below 35 K. A number of physical experiments are presented, where the authors had the means to take quantitative measurements of the heat leak caused by these pressure oscillations in apparatus with bent tubes ranging from 4.55 and 4.7 mm inner diameter, with heat stationing links. The parameters which indicate the likelihood of inadvertently developing these thermoacoustic oscillations are presented and means developed to avoiding them in that instance are given. Furthermore, we had the rare opportunity to record and analyze 4 K TAOs experienced on a test setup and present the simple method that was used to eliminate them.

1. Introduction

When designing a cryostat or a constituent component that will be installed in a cryostat (e.g. an insert with tubing) one turns to well-established cryogenic practices and guidelines to define how the cryostat has to be built. Nowadays, we have good field proven design tools at hand to analyze heat sources enabling very accurate minimum boil-off designs with reduced heat leaks [1]-[12].

Sometimes however, the desired cryostat functionality forces the engineer to compromise and introduce non ideal cryogenic components, for example if one uses small diameter tubing it is known that the likely risk of creating thermoacoustic oscillations (TAOs) is increased. Ideally of course one would not employ such components but for other reasons one may be forced to use them. In those cases, the engineer needs to be fully aware of the likely risk at the design stage, and what the consequences of that risk are in order to decide whether to accept the consequence and plan ahead accordingly to minimize the impact of TAOs on the thermal budget and program schedules.

This dilemma has also been mentioned previously by Luck and Trepp: “Very often, geometry of operating conditions cannot be selected freely, and systems capable of oscillations have to be built” [13]-[15]. As Rose-Innes [16] more succinctly describes it: “If the supporting tubes are not evacuated but contain helium gas there is a possibility that thermal oscillations may arise inside them. It is surprising how easily these oscillations occur. Usually this is not a problem as long as holes can be drilled into the cold end tube. If the tube is exposed to vacuum however, the problem is more elaborate to solve.”

In the following examples case studies are given showing the onset of several unexpected thermoacoustic oscillations, that – according to well-established cryogenic practices and guidelines – should not have been present.

2. Case study 1: TAOs on a gas connecting line from 300 K to 25 K

Whilst most of the oscillations noted in engineering are of spontaneous nature [1], in this example the authors are reporting a non-spontaneous “driven” thermoacoustic oscillations of transient nature, which occurred on a helium gas tank inlet line in which no liquid was present. Figure 1 shows the schematics of the layout.

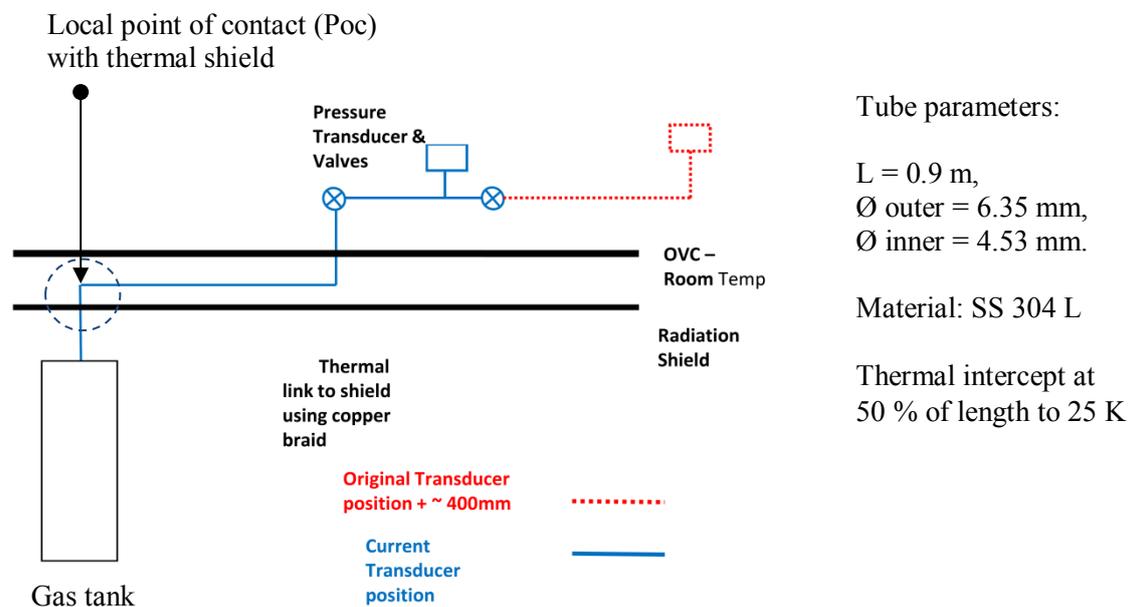


Figure 1. Schematics of the gas tank inlet line.

The figure above depicts a gas tank located in a cryostat fitted with pressure transducers and valves and with tubing extending vertically up from the gas tank, passing horizontally through a thermal shield and leaving the cryostat vertically through the outer vacuum case (OVC) top plate. The horizontal gas feed tube was locally heat stationed at 35K to the thermal shield (radiation shield) as shown.

The dotted line shows the original location of the pressure transducer at room temperature. For other reasons it was deemed necessary to shorten the total tube length, and relocate the pressure transducer between two needle valves. When this change was implemented it was noticed that when heating the gas tank, the following transient behavior was observed (again note that there is only helium gas in the gas supply tank and no liquid contact surface, it is sometimes wrongly assumed that oscillations only occur when liquid helium is present).

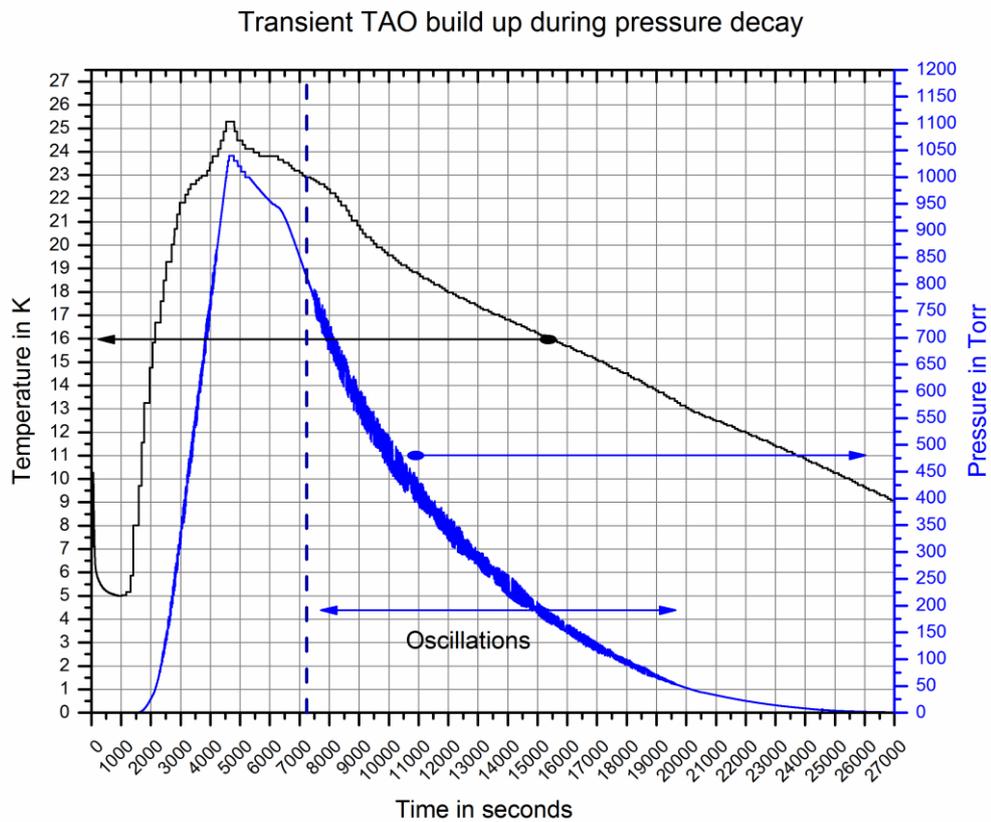


Figure 2. Transient pressure decrease initiating non-spontaneous thermoacoustic oscillations.

During a particular operational sequence the gas tank needs to be temporarily heated from 5 to 25 K, this causes the gas tank pressure to rise and then fall after heating is stopped as the gas tank is allowed to cool down. It is during this process the pressure fluctuations were discovered and external pipe frosting observed (Figs 2 and 3). In a correctly heat stationed system (employing standard cryogenic practices and guidelines) the transient appearance of frosting like this is likely evidence of unforeseen TAOs, here one can clearly see the frosting on the tubing and the attached valve.



Figure 3. Frosted tube at relief valve, indicating presence of thermoacoustic oscillations.

The presence of TAOs has associated with them unforeseen parasitic heat loads, consequently any operational changes to a cryostat or its room temperature connections need to be analyzed in detail to look at the likelihood that these changes will push the system into a region of instability.

The method to do this is to use a stability map for the cryogen (helium) and calculate a number of parameters for the given system which will allow the engineer to infer where his system sits on the stability map, the calculations can be repeated for any system changes to see where the system moves on the stability map. A good example is also found in Hands [17].

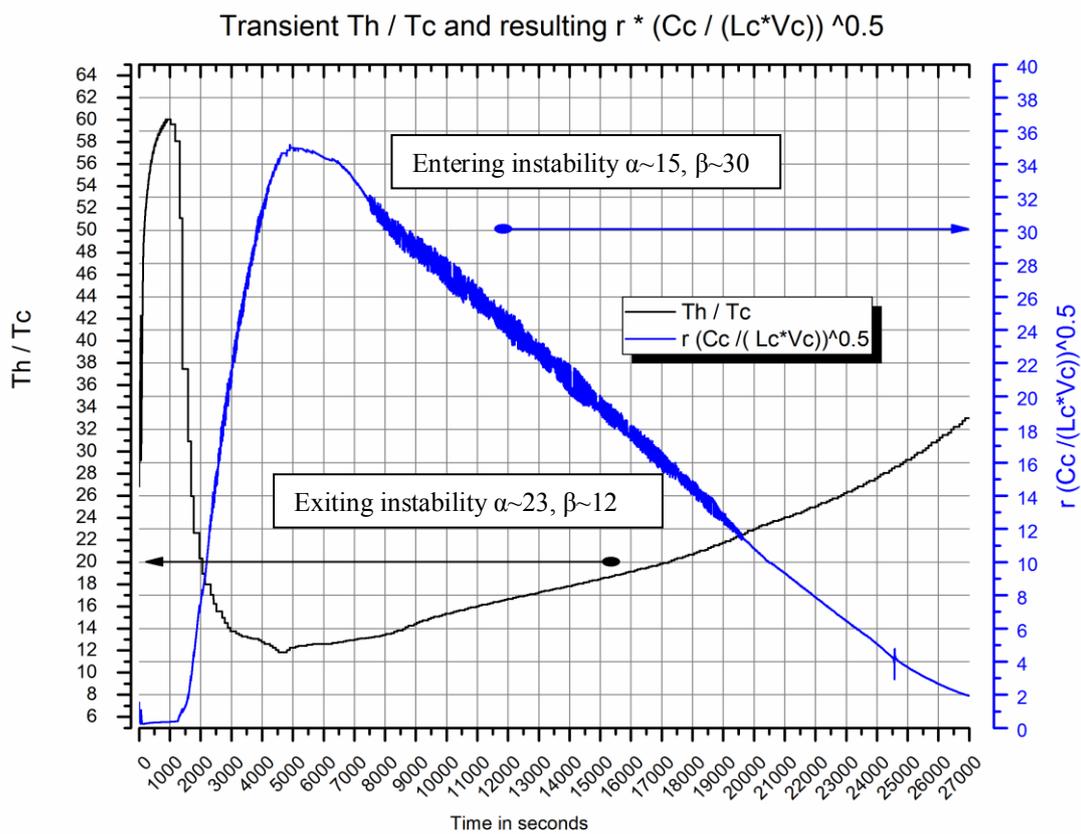


Figure 4. Calculated stability parameters.

For the above example, the transient values $\alpha = T_h / T_c$ and $\beta = r * (c_c / (l_c * v_c))^{0.5}$ are calculated as shown in Figure 4. This data was then fitted into the stability map for helium with $\xi = 0.5$ in all cases, whereas ξ is the ratio of hot end / cold end tube length. Figure 5 shows how upon completing the initial heating of the gas tank we quickly move towards the unstable region as the pressure is lowered and the heater is switched off. The TAOs did not start suddenly but showed a slow increase as the unstable region was reached. The squares in Figure 5 relate to the oscillations shown in Figures 2 and 4, here we can clearly see the system track through the unstable region and reemerge on the other side where the oscillations stop. The measurements although not exact show a good correlation with entry and exit from the instability region.

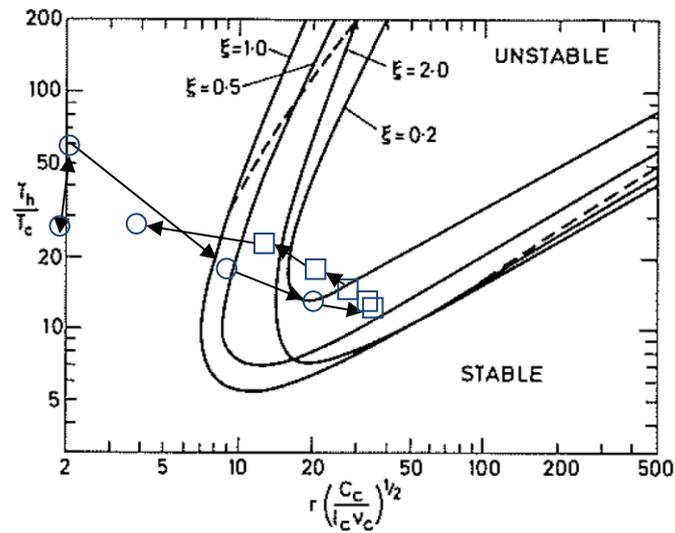


Figure 5. Transient TAOs in the stability map, timing as per Figures 2 and 4 (circle, no oscillation, square, oscillation, arrow shows the transient move).

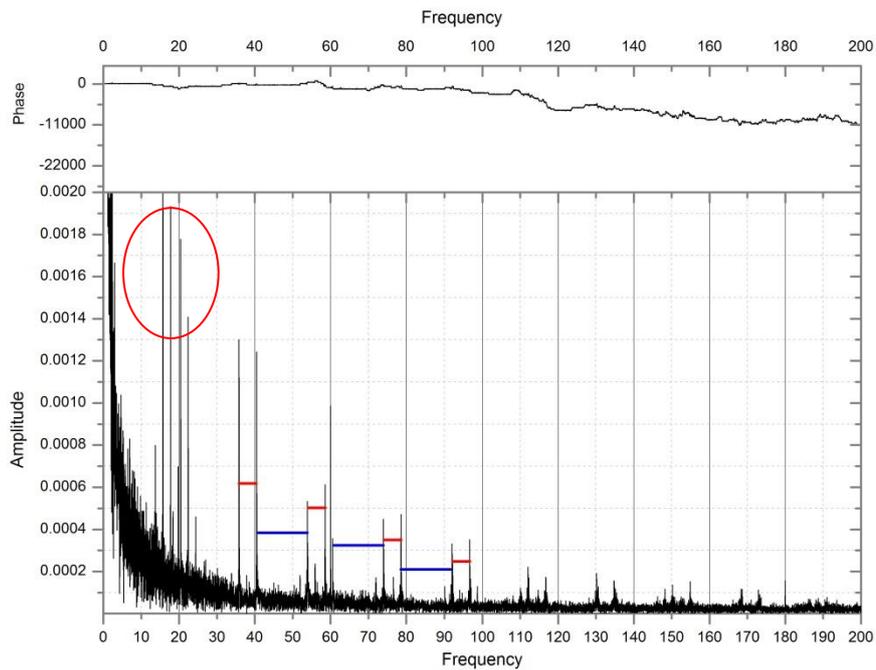


Figure 6. FFT analysis at 100 Torr.

To rectify the problem the system resonance was changed as follows. An FFT was performed on the pressure recordings (example shown for 100 Torr) to identify the main resonant peaks. A Helmholtz damper [13] was proposed to move the system away from the resonances. Impedance calculations for a Helmholtz damper design were proposed for the lowest 35 Hz frequency at the highest peak [15], [18]. Due to the space restrictions a coiled tube reservoir connected to an adjustable

orifice (needle valve) with a dead end was physically used to act as an impedance part instead of a Helmholtz damper, as proposed by Luck [15]. A consecutive FFT analysis showed that with the damped setup the TAOs were still present in this frequency range but the higher amplitudes were clipped. This was enough to significantly reduce and control the heat loads that were previously observed. Note that after the damper was fitted the tubing did not frost also confirming the heat load reduction. This approach was chosen since it was simple to implement and by turning the needle valve the optimum position that corresponds to a specific orifice size the resonance could be easily tuned allowing the system to tolerate a band of likely resonants in future. In this example TAOs were noticed only after the transducer in Figure 1 was moved to a different position shortening the hot length of the tube as a result of design constraints.

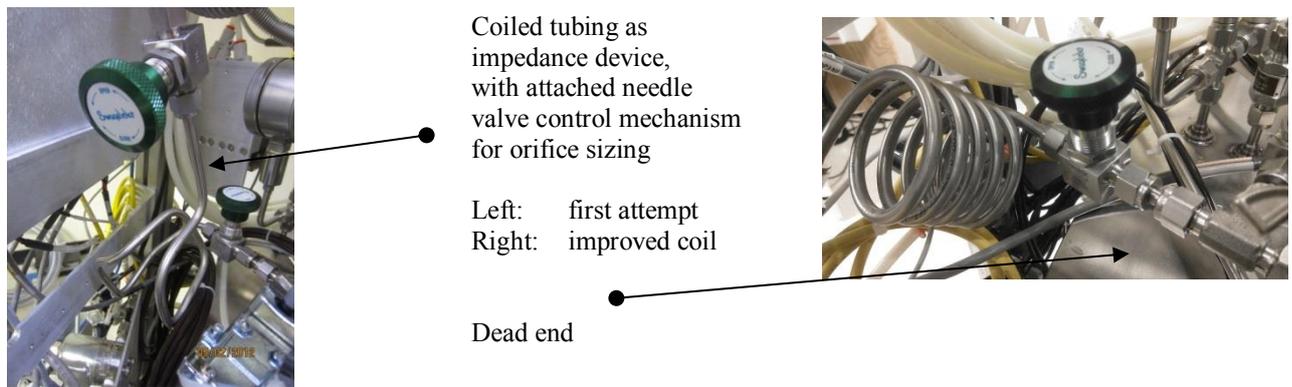


Figure 7. Coiled tube with adjustable orifice (valve) and dead end.

3. Case study 2: TAOs at cold end temperature of a guide tube at 0.77 K

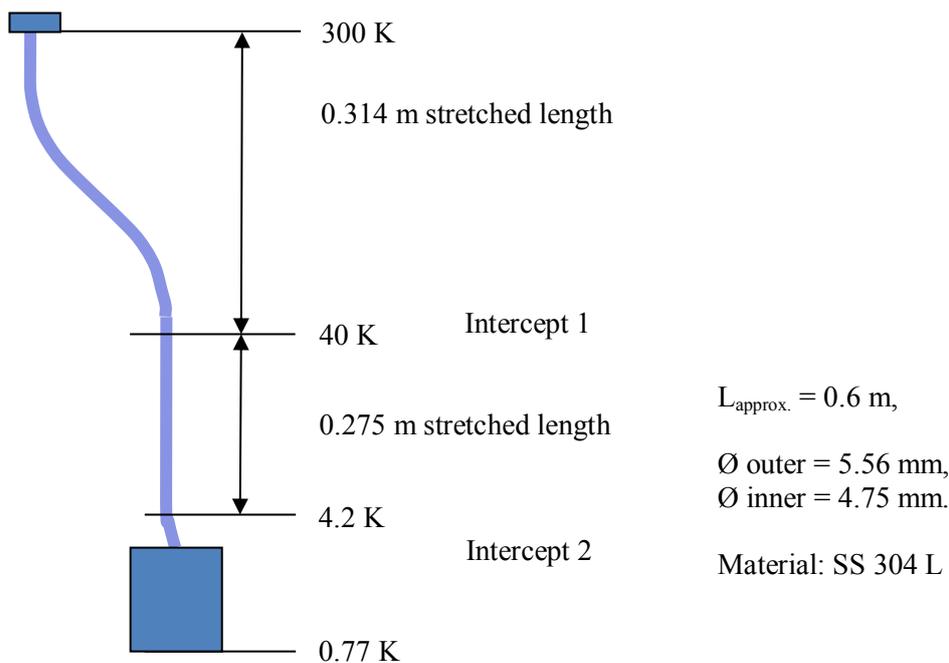


Figure 8. Curved tube in cryostat, oscillation prone, extending into a 0.77 K helium bath.

Case 2 shows a curved tube leading from room temperature down to a superfluid helium bath maintained at 0.77 K. The tube without heat intercepts was suspected to oscillate based on its small diameter and respective boundary conditions, this behavior has been long observed since the early work by Taconis et al in 1949 [19]-[21].

In order to understand this problem existing literature was reviewed. Surprisingly, literature and data for experimental results on TAOs for specific tubes are generally difficult to obtain. However, Gu in [22], [23] was reporting some experimental results with a straight non-intercepted tube of similar geometry. The corresponding test tube length of Gu was 1.2 m, close to the one in this setup. The test radius by Gu was 2.48 mm with a wall thickness of 0.2 mm, whereas the tube for this case 2 was 0.4 mm. When the system stability parameters were calculated basically all length ratios showed that thermoacoustic oscillations are highly likely. As an aside this is in good agreement with what one observes when inserting the straight tube / flange into a helium dewar using it as a “thumper” dipstick. The implication is TAOs will always be present in this design unless the thermal profile of the system is modified. For example by fitting a thermal heat sink at the right position one can modify the stability by changing α .

This is not an ideal solution because even after placing the intercepts it is found the system is still close to the stability line envelope. During the assembly stages thermal link locations can change and even a small amount could be enough to push a system into instability. Any incident TAOs could then not be suppressed since the thermal link is too close to the unstable region at the hot end (see Table 1 (values with asterisk) when taking the values into Figure 5) causing a higher than normal heat flux down the tube to the 0.77 K liquid helium bath.

Table 1. Stability parameters for Figure 8.

Variable name	Variable	Hot end	Cold end 1	Unit
Temperature, hot end	T_h	300	40	K
Temperature, cold end	T_c	40	5	K
$\alpha = T_h / T_c$ *	-	7.5	8	-
$\xi = L_h / L_c$	-	0.12	0.58	-
Pressure	p	$1 \cdot 10^{+05}$	$1 \cdot 10^{+05}$	Pa
Tube internal radius	r	0.002375	0.002375	m
Cold length	l_c	0.39	0.275	m
velocity of sound	C_c	373.40	119.70	m/s
Dynamic viscosity	η	$5.542 \cdot 10^{-06}$	$1.388 \cdot 10^{-06}$	Pa s
Density	ρ	1.2004	11.78	kg/m ³
Kinematic viscosity	ν_c	$4.6168 \cdot 10^{-06}$	$1.179 \cdot 10^{-07}$	m ² /s
$\beta = r * (c_c / (l_c * \nu_c))^{0.5}$ *	-	34.202	144.31	-

One may now enquire whether any production designs like this is always safe against the presence of TAOs even if the system was designed to avoid them. In general the answer is most likely no, not always. During assembly, the position of thermal intercepts may change that then lead to oscillations. But there is yet another example which shows the unexpected development of TAOs over time.

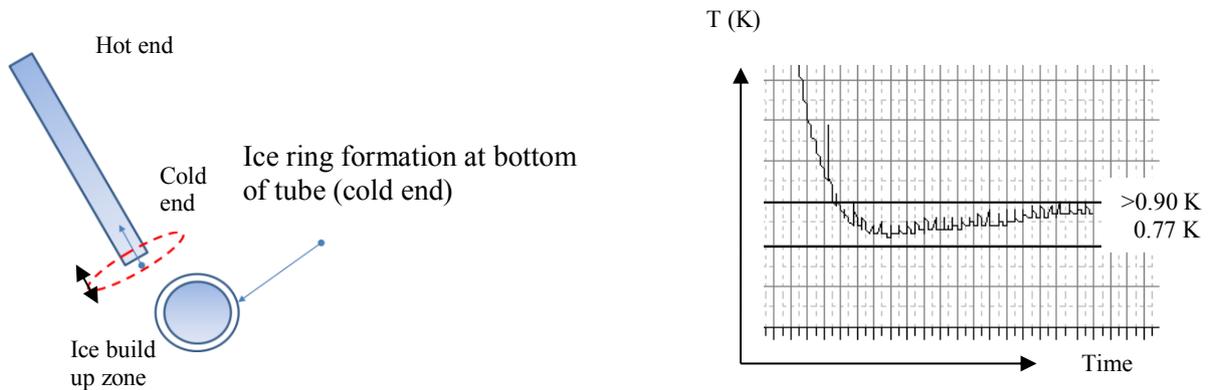


Figure 9. Left: Cold tube end as in Figure 8 during ice formation, right: base temperature increase.

The formation of an ice ring at the coldest spot, e.g. at the tube entry can cause the onset of TAOs in the device attached to the tube, similar as shown in Figure 9. Ice formation in turn leads to an increase in superfluid film creep speed (roughened tube surface) and introduces a permanent parasitic heat load to the 0.77 K bath as shown in Figure 9, causing a steady temperature drift over time.

As can be seen from Table 1 a tube that is e.g. 10 times smaller in radius rapidly changes from its stability region $\beta=(144.31)$ toward the unstable region $\beta=(14.43)$. Further experiments need to be carried out to show whether a tube with a constriction or a reduced openness near the tube bottom end can in fact be treated as a tube with reduced diameter along its whole cold length, but this is suspected to be the case. The same effect is seen when air ingress at the hot end of a cold tube freezes out at the 40 K link position. The reduced tube diameter at the 40 K link is capable of introducing a similar oscillation on the 0.77 K bath.

4. Case study 3: TAOs on a test set up tube at 4.2 K and with wide 20 mm tube diameter

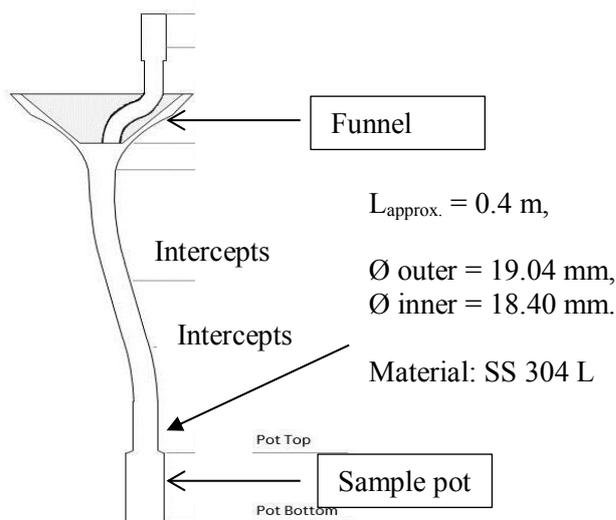


Figure 10. Slightly curved tube with closed funnel extending to a 0.77 K helium bath.

Figure 10 shows a bent vertical tube with an extended hot end closed funnel region. Since the tube extends from 300 K to 0.77 K and is known to exhibit TAOs on the 0.77 K bath multiple thermal links need to be introduced to avoid oscillations and to limit the heat load to the reservoir despite the funnel shaped top end. TAOs have been recorded in the presence of ice at the bottom of the sample pot as well as at the sample pot top flange causing the sample pot temperature rise in some cases well above its superfluid regime. There is currently no stability map that would predict TAOs in the 0.77 to 4 K region. Figure 11 shows the significant response to TAOs of both low temperature sensors in the superfluid reservoir. The remedy here is to keep the pot clear of any ice.

NMR cryostat designs with this tube diameter are known to occasionally cause TAOs which then require fitting of Helmholtz dampers. This could either be the traditional orifice fitted resonance tube or even a metal foam filled device.

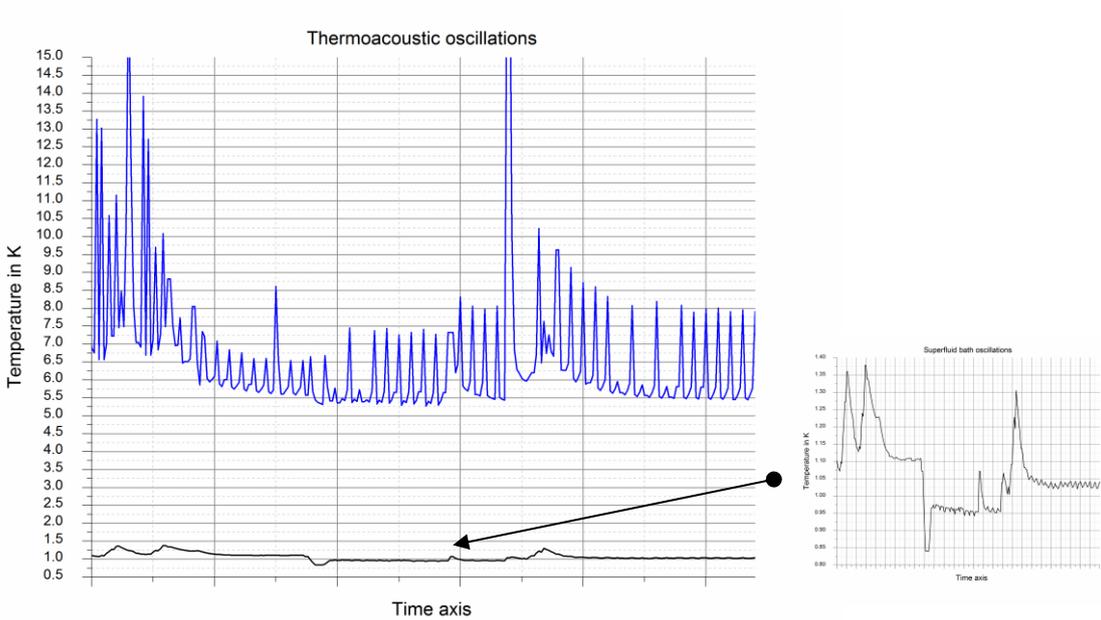


Figure 11. Influence of thermoacoustic oscillations on a superfluid helium bath and above.

5. Case study 4: TAOs on a test setup at 4.2 K

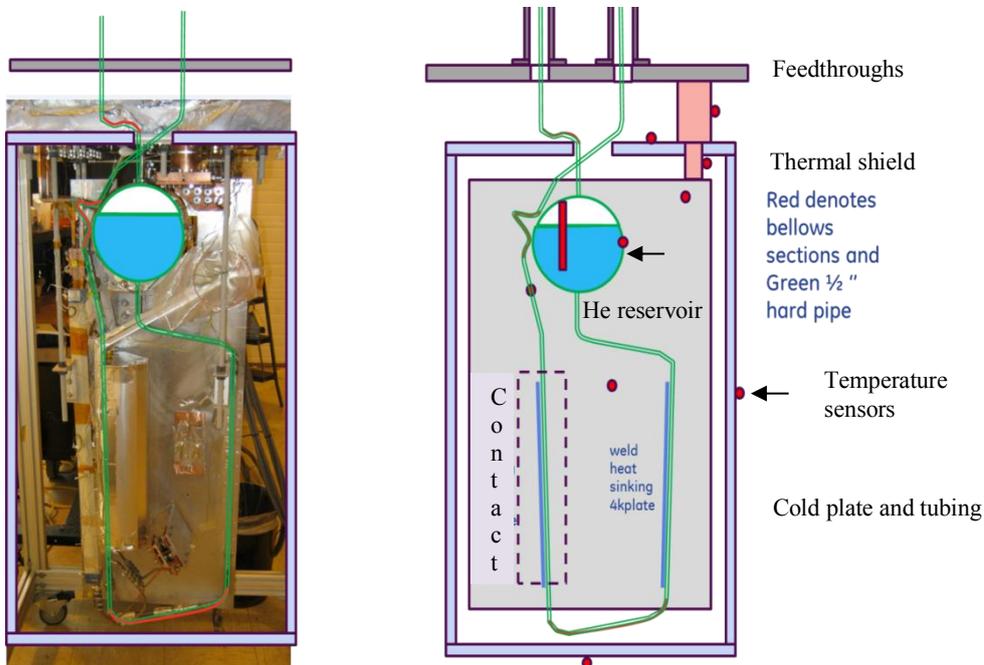


Figure 12. Schematic test setup with tube routing fixed to a 4 K aluminum cold plate.

Figure 12 shows a cryogenic component test facility. The components are mounted and heat-sunk on a rectangular cold plate. All tubing is routed at room temperature by means of vacuum feedthroughs to a liquid helium reservoir. The design was assumed to be safe but this system exhibited TAOs on its first cooldown. After the fact the system was analyzed. Table 2 shows the stability parameters calculated for the design. The TAOs arose in the system as the liquid level in the tank dropped below 20 - 30%, this behavior was repeated on subsequent runs. The consequence was an additional heat load on the system cold plate which forced a ΔT rise from 4.05 to approx. 4.6 K and which made it impossible to conduct long duration experiments. The solution here was to divide the piping into 2 temperature regimes making a strong, reliable and extended heat sink at the thermal shield top plate, forcing the system to remain in a stable regime eliminating temperature fluctuations.

Table 2. Stability parameters for Figure 12.

Variable name	Variable	No intercepts	Regime 1	Regime 2	Unit
Temperature, hot end	T_h	300	300	54	K
Temperature, cold end	T_c	4.5	54	4.6	K
$\alpha = T_h / T_c$	-	66.66	5.55	11.74	-
$\xi = L_h / L_c$	-	0.5	0.5	0.5	-
Pressure	p	$1 \cdot 10^{+05}$	$1 \cdot 10^{+05}$	$1 \cdot 10^{+05}$	Pa
Tube internal radius	r	0.00585	0.00585	0.00585	m
Cold length	l_c	0.5	0.5	0.5	m
velocity of sound	C_c	108.36	433.53	110.87	m/s
Dynamic viscosity	η	$1.292 \cdot 10^{-06}$	$6.669 \cdot 10^{-06}$	$1.312 \cdot 10^{-06}$	Pa s
Density	ρ	14.25	0.8894	13.645	kg/m ³
Kinematic viscosity	ν_c	$9.069 \cdot 10^{-08}$	$7.4984 \cdot 10^{-06}$	$9.612 \cdot 10^{-08}$	m ² /s
$\beta=r*(c_c/(l_c*\nu_c))^{0.5}$	-	285.97	62.91	28.10	-
Regime status	-	Unstable	Stable	Stable	-

6. Conclusion

Even though engineers have practical methods to avoid the likelihood of developing TAOs in cryostats at the design state, for simple tube geometries and configurations thanks to the theoretical and experimental work done and the available data, TAOs can still occur unexpectedly as shown. They are a dynamic phenomenon occurring as the temperature and pressure fluctuations move the system into an instability regime.

Based on this work the following observations and recommendations regarding the onset of TAOs can be made:

- Transient TAOs can appear depending on pressure and temperature changes, e.g. at cooldown even with no liquid present,
- they can show up in bent shaped as well as horizontal tubes; research so far has only looked at straight tubes,
- they can show up because of unforeseen design changes, for example changes to the room temperature piping at the hot end,
- the cold end tubing does not necessarily need to be in contact with a liquid surface to develop TAOs,
- for the first time, parasitic heat loads due to oscillations have been recorded between 4.2 K (hot end) and 0.77 K (cold end),
- they can develop over time for example if the bottom tube radius decreases due to ice formation or they can be excited if the cold end is fitted with a constriction, e.g. an orifice that decreases the tube entrance radius,
- they momentarily show up in tubes properly heat stationed and wide tube diameter, if the bottom tube end radius is reduced in an insertion process,
- heat intercepts are used to control heat loads, but TAOs are also well-controlled by optimally placed thermal intercepts,
- a system can still run into TAOs if the location of those intercepts is slightly changed, for situations where the system is near an unstable/stable region,
- Unfortunately stability regions are not predicted exactly however they are a good indicator of the likelihood of incurring TAOs. It is suggested that introducing a “safety margin” is

advisable when using this technique in the design process, especially when not all operating conditions are known yet.

In most cases the use of Helmholtz dampers can eliminate TAOs, when properly designed, sometimes this is not feasible or leads to increased cost and complexity. It is therefore highly advisable to scrutinize and scan the complete tubing circuit for TAOs early at the design stage since those are sometimes not evident as shown here, but could explain why your total heat balance calculation does not fully agree with theory. Further research in this field is needed to obtain data on the occurrence of TAOs in more complex shaped tubes and boundary conditions.

Acknowledgments

The authors wish to acknowledge Neil Clarke and Howard Jones at Oxford Instruments Omicron Nanoscience for many fruitful discussions on this topic and the support of the technical team at GE Global Research.

References

- [1] Rott N 1969 Damped and thermally driven acoustic oscillations in wide and narrow tubes *ZAMP* **20** 230-43
- [2] Rott N 1973 Thermally driven acoustic oscillations, Part II: stability limit for helium *ZAMP* **24** 54-72
- [3] Rott N 1975 Thermally driven acoustic oscillations, Part III: second-order heat flux *ZAMP* **26** 43-49
- [4] Rott N and Zouzoulas 1976 G Thermally driven acoustic oscillations, Part IV: tubes with variable cross-section *ZAMP* **27** 197-224
- [5] Zouzoulas G and Rott N 1976 Thermally driven acoustic oscillations, Part V: gas-liquid oscillations *ZAMP* **27** 325-34
- [6] Müller U and Rott N 1983 Thermally driven acoustic oscillations, Part VI: excitation and power *ZAMP* **34** 609-26
- [7] Hofmann v T et al 1973 Experiments on thermally driven gas oscillations *Cryogenics* **13** 490-2
- [8] Thullen P 1968 Model for thermally sustained pressure oscillations associated with liquid helium *Adv. In Cryog. Eng.* **13** 215-22
- [9] Bannister J D 1966 Spontaneous pressure oscillations in tubes connecting liquid helium reservoirs to 300 K environments in Liquid Helium Technology: *Proceedings of the International Institute of Refrigeration Commission 1* Boulder 127-135
- [10] Gaffney J and Clement B 1955 Liquid Helium Level-Finder *Rev. Sci. Instrum.* **26** 620
- [11] Gary J 1988 A numerical method for acoustic oscillations in tubes *International journal for numerical methods in fluids* **8** 81-90
- [12] Liburdy J A and Wofford J 1979 Acoustic Oscillation Phenomena in Low-velocity steady flow with heating *Adv. In Cryog. Eng* **35** 528-40
- [13] Luck H and Trepp C 1992 Thermoacoustic oscillations in cryogenics, Part 1: basic theory and experimental verification *Cryogenics* **32** 8 690-7
- [14] Luck H and Trepp C 1992 Thermoacoustic oscillations in cryogenics, Part 2: applications, *Cryogenics* **32** 8 698-702
- [15] Luck H and Trepp C 1992 Thermoacoustic oscillations in cryogenics, Part 3: avoiding and damping of oscillations *Cryogenics* **32** 8 703-6
- [16] Rose-Innes A C 1964 Low temperature techniques van Nostrand
- [17] Hands B 1986 Cryogenic Engineering Academic Press
- [18] Tward E and Mason P V 1982 Damping of thermoacoustic oscillations *Adv. In Cryog. Eng.* **27** 807-15
- [19] Taconis K W 1949 Measurements concerning the vapour-liquid equilibrium of solutions of He³

in He⁴ below 2.19 K *Physica XV* **8-9** 733-9

- [20] Kramers H A 1949 Vibration of a gas column *Physica XV* **11-12** 971-84
- [21] Edwards M H and Woodbury W C 1960 Condensation of supersaturated He⁴ vapor in a cloud chamber *Can. J. Phys.* **38** 3 335-45
- [22] Gu Y 1993 Thermal acoustic oscillations in cryogenic systems University of Colorado PhD thesis
- [23] Gu Y and Timmerhaus K 1994 Experimental verification of stability characteristics for thermal acoustic oscillations in a liquid helium system *Adv. In Cryog. Eng.* **39** 1733-40