Design Guidelines for Avoiding Thermo-Acoustic Oscillations in Helium Piping Systems

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Abstract

Thermo-acoustic oscillations are a commonly observed phenomenon in helium cryogenic systems, especially in tubes connecting hot and cold areas. The open ends of these tubes are connected to the lower temperature (typically at 4.2 K), and the closed ends of these tubes are connected to the high temperature (300K). Cryogenic instrumentation installations provide ideal conditions for these oscillations to occur due to the steep temperature gradient along the tubing. These oscillations create errors in measurements as well as an undesirable heat load to the system. The work presented here develops engineering guidelines to design oscillation-free helium piping. This work also studies the effect of different piping inserts and shows how the proper geometrical combinations have to be chosen to avoid thermo-acoustic oscillations. The effect of an 80 K intercept is also studied and shows that thermo-oscillations can be dampened by placing the intercept at an appropriate location.

Keywords: Helium Piping, Thermo-acoustic Oscillations, Cryogenic Systems

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1. Introduction

Cryogenic systems are very susceptible to thermal-oscillation instabilities. When a gas column in a long cylindrical tube is subjected to strong temperature gradients, it may spontaneously oscillate with large amplitudes. These thermo-oscillations are generally called Taconis oscillations. These Taconis oscillations are most problematic in helium cryogenic systems where one end of a tube is at liquid helium temperature and other end of the tube is at ambient temperature. These oscillations can result in an enormous heat flux at the cold end, up to 1000 times greater than the tube conduction itself [1]. Rott [2] successfully generated the stability curves for oscillations in helium systems, predicting the oscillating and non-oscillating zones. Rott discovered that there are two branches of the curve, a lower branch and an upper branch. Both of these branches join at a single point below which there are no excited oscillations. He also concluded that the upper branch of the stability curve does not have any practical significance because of the excessively high temperature ratios required.Today, these curves serve as a primarily design criteria to identify or predict where oscillations will occur. The phase diagram generated by Rott has also been verified experimentally by many researchers [1, 3]. They all concluded that cryogenic oscillations can be predicted with reasonable accuracy with the help of the Rott stability curves.

The stability curve generated for helium gas indicates that thermal oscillations can be avoided if proper attention is paid during the design stage. Certain combinations of tube length and tube inner diameter will result in an oscillation-free system. Moreover,any existing thermal oscillations in the system can be dampened by altering the operating temperature ratio between the hot and cold ends by providing an 80 K intercept. The location of this intercept must be chosen carefully.

To the best knowledge of the present authors, there are no clear, simple, and ready to use design guidelines existing in literature to design oscillation-free helium piping. Furthermore, it is also not straight-forward to determine acceptable length-diameter combinations based on the present available literature.Therefore, the present work is aimed at describing engineering design guidelines for helium piping systems to avoid thermal oscillations. Stability-limited length and inner diameter combinations have been generated using the Rott mathematical model. The present work is also extended to formulate the design guidelines in the presence of tube inserts, describing how to choose acceptable length-diameter combinations to result in an oscillation-free system. The appropriate location of an 80 K intercept to dampen oscillations in a tube with one end at 300 K and the other end at 4.2K is also analyzed as a function of tube length and inner diameter.

2. Analysis

Figure 1 shows a typical arrangement of helium piping with one end at 4.2 K and the other end at 300 K. It is assumed that the tube is filled with helium gas at 1 bar absolute pressure. The helium gas column confined in the tube is assumed to be oscillating.

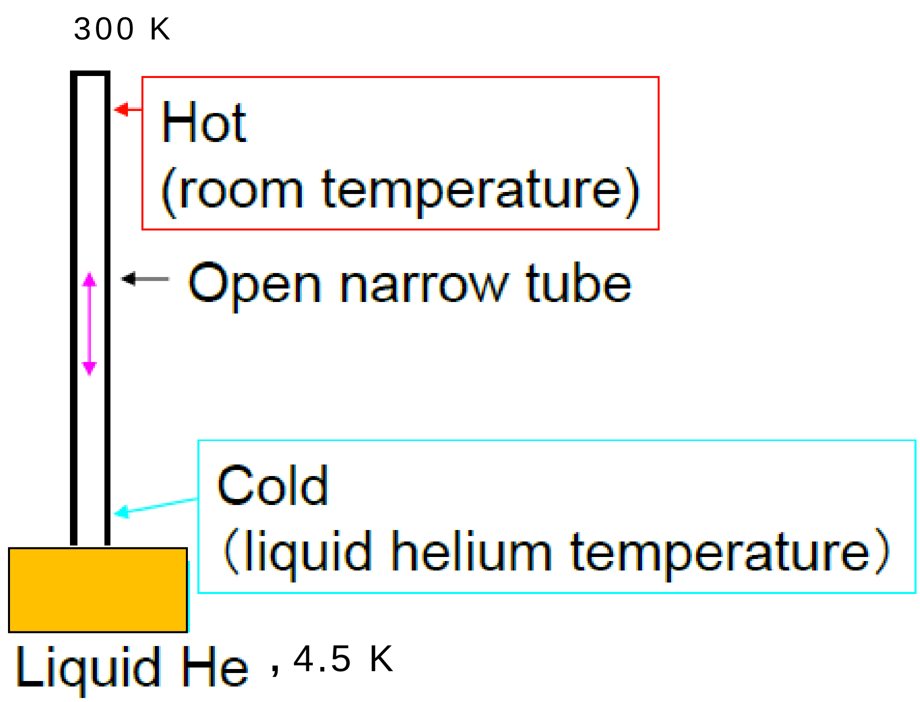

Figure 1: Typical example of a helium piping system.

According to Rott's theory, the optimum position of the temperature jump for excited oscillations lies near the middle of the half-open tube and remains practically unaffected up to a hot-to-cold length ratio of 2:1. Therefore, the present analysis is based on the assumption that this temperature jump occurs at the centre of the tube as shown in Figure 2. From a closer look at the Rott stability curves, it can also be said that assuming this temperature jump occurs at the centre will always produce conservative design criteria for given temperature ratios.

To illustrate the position of this temperature jump mathematically, it can be seen from Figure 2 that at x = 0, the tube is open and it will have a constant temperature T_L between x=0 and x = l. At x = L, the tube will be closed and it will be at constant temperature T_H between x = l and x = L. The position of the temperature jump can be given mathematically as the ratio of hot end tube length to cold end tube length and can be expressed as

$$\xi = \frac{L-l}{l} \tag{1}$$

In the present analysis, a constant ξ = 1 is used by assuming the temperature jump occurs at the centre.

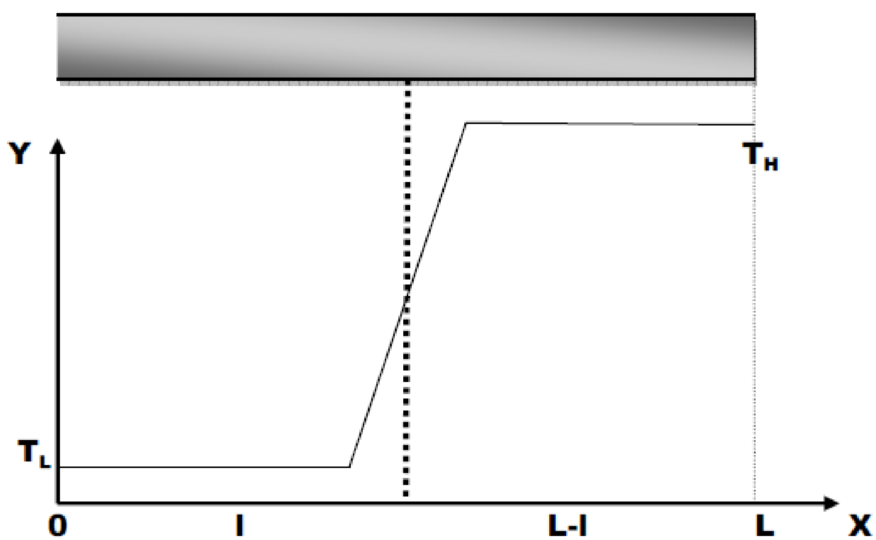

Figure 2: Illustration of temperature distribution along the tube

The goal of this document is to develop an analysis and useful guidelines which can be directly applied to the practical purpose of designing oscillation-free helium piping systems or damping out oscillations in existing helium piping systems. The lower branch of the Rott stability curve is used for the analysis, and this stability curve is generated using the Equation 18 from Ref. [2]

$$Y_c = \frac{2D\alpha^{1+\beta}}{\left(1+\xi^{-1}+\lambda_c^2\xi\right)} \tag{2}$$

where α is the hot-to-cold temperature ratio expressed as

$$\alpha = \frac{T_H}{T_L} \tag{3}$$

The value of λ_c in Eq. (2) is given by

$$\lambda_c = \frac{\omega l}{a_c} \tag{4}$$

where ω is the angular frequency, a_c is the sound speed in the gas, and l is the tube cold length.

The other constants used in Eq.(2) are D = 1.19, β= 0.647 for helium, and ξ =1.0 as discussed earlier. The stability curve generated from Eq. (2) for λ_c =1.0 is shown in Figure 3.

The stability limit Y_c calculated from Eq. (2) is in excellent agreement with numerical values plotted in Figure 3 of Ref. [2]. Therefore Eq. (2) can be directly used to get the stability limit for different temperature ratios α.

The physical phenomena underlying the driving potentials of thermo-acoustic oscillations in tubes depend on the viscous action of the fluid on the tube surfaces. Thermo-physical properties of the fluid and geometric parameters of the tube, such as length and inner diameter, play a crucial role propagating or damping these oscillations. One of the parameters controlling the amplitude of a Taconis oscillation is given by

$$Y_c = \frac{d_o}{2}\left[\frac{a_c}{l\upsilon_c}\right]^{\frac{1}{2}} \quad (5)$$

where d_o is the tube inner diameter and υ_c is the kinematic viscosity of the gas.

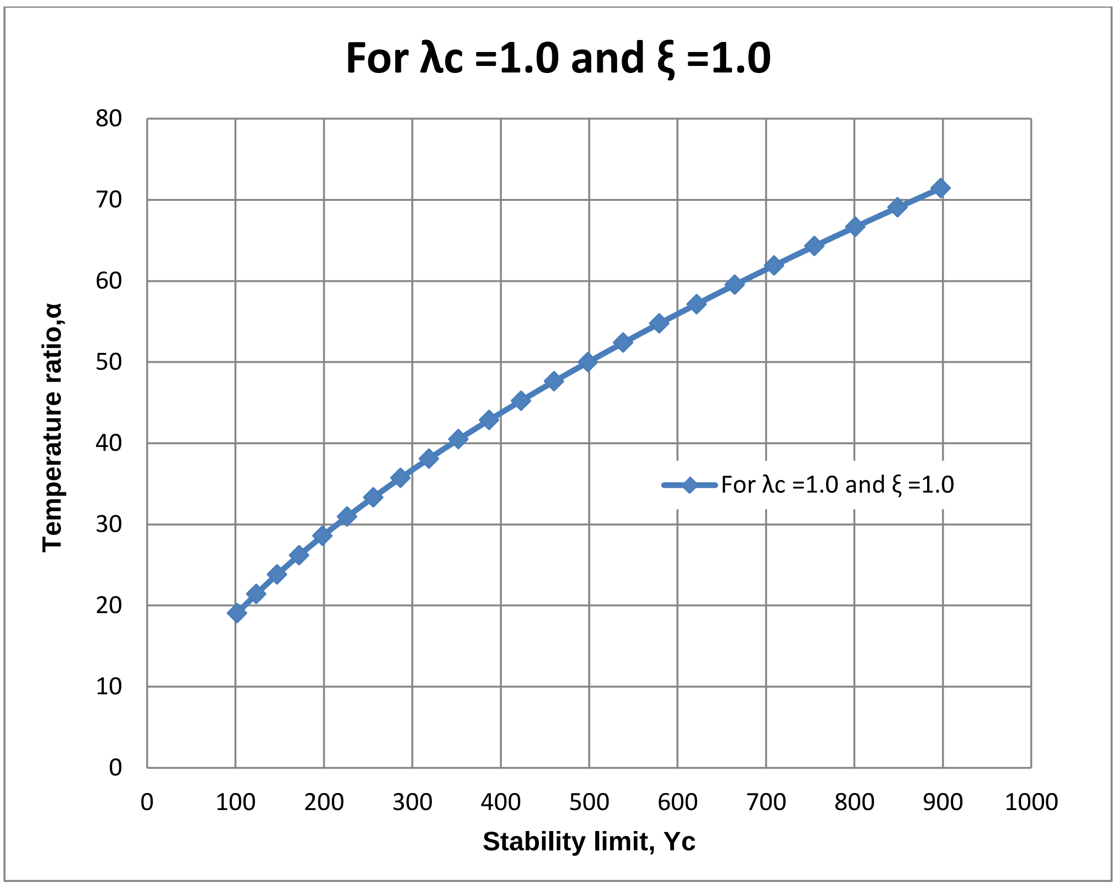

Figure 3: Lower stability curve from Eq.(2)

The dimensionless parameter Y_c for stability given in Eq.(5) can be directly compared to Eq. (2) to set the critical limit of tube inner diameter for a given tube length and temperature ratio. Therefore

$$\frac{d_o}{2}\left[\frac{a_c}{l v_c}\right]^{\frac{1}{2}} = \frac{2D\alpha^{1+\beta}}{\left(1+\xi^{-1}+\lambda_c^2\xi\right)} \tag{6}$$

$$d_{o,critical} = \frac{4D\alpha^{1+\beta}}{\left(1+\xi^{-1}+\lambda_c^2\xi\right)}\left[\frac{l v_c}{a_c}\right]^{\frac{1}{2}} \tag{7}$$

The critical tube inner diameter given by Eq.(7) is an important parameter. Its practical significance and how it is useful in the piping design will be discussed in the upcoming section of this report.

The present analysis also studied the effect of inserts in the tube. If the insert inner diameter is d_i, Eq.(7) can be modified as follows

$$d_{o,critical} = \frac{4D\alpha^{1+\beta}}{\left(1+\xi^{-1}+\lambda_c^2\xi\right)(1-\chi)}\left[\frac{l v_c}{a_c}\right]^{\frac{1}{2}} \tag{8}$$

where $= \frac{d_i}{d_o}$.

3. Results and Discussion

Based on the analysis presented in the above section,occurrence of thermo-acoustic oscillations for different tube length-diameter combinations can be mapped. This mapping can be directly applied by the designer for choosing a tube length-diameter combination so that the system will be oscillation-free. Figure 4 shows such a mapping diagram for different length-diameter combinations of practical interest.

Figure 4 displays the results for two cases. In the first case,one end of the tube is at 300 K and the other end is at liquid helium temperature (~4.2K). In the second case, one end of the tube is at 80K and the other end is at liquid helium temperature (~4.2K). This figure shows two zones, oscillating and non-oscillating, for certain length-diameter combinations of the tube. One can quickly find from Figure 4 which length-diameter combinations will fall in the oscillating zone. For example, if one selects a 1 m length of instrumentation tubing to be connected between 300 K and 4.2 K, then a tube inner diameter greater than 15 mm is required to ensure the helium piping will be oscillation-free.

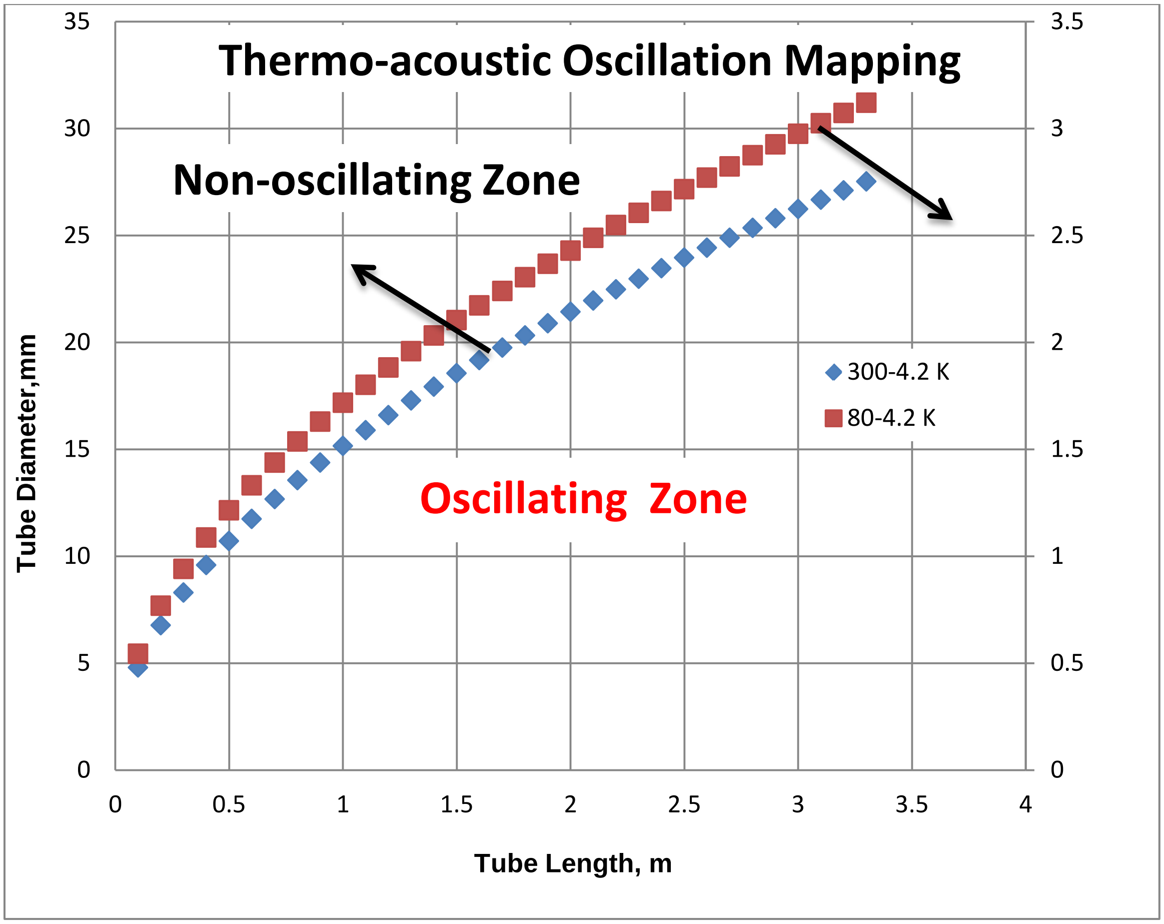

Figure 4: Thermo-acoustic oscillation mapping for different length-diameter combinations.

In cryogenic instrumentation piping, different kinds of inserts are used to reduce the effective volume inside the piping. Examples of common inserts are copper wires and nylon fish lines. Usage of inserts should be considered during piping design. Figure 5 maps the oscillating and non-oscillating zones for different length-diameter combinations when tube inserts are used. It shows that the combination of tube length and tube inner diameter should be selected based on what percentage of the tube inner diameter is occupied by inserts. For example, if 50% of the tube inner diameter (25% of the gas space cross-section in the tube) is occupied by inserts, one must select a tube inner diameter greater than 40 mm to ensure that a 1.5 m long tube will be oscillation-free. If inserts occupy 80% of the tube inner diameter (64% of the gas space cross-section in the tube), one must select a tube inner diameter greater than 90 mm to ensure that the same 1.5 m long tube will be oscillation-free.

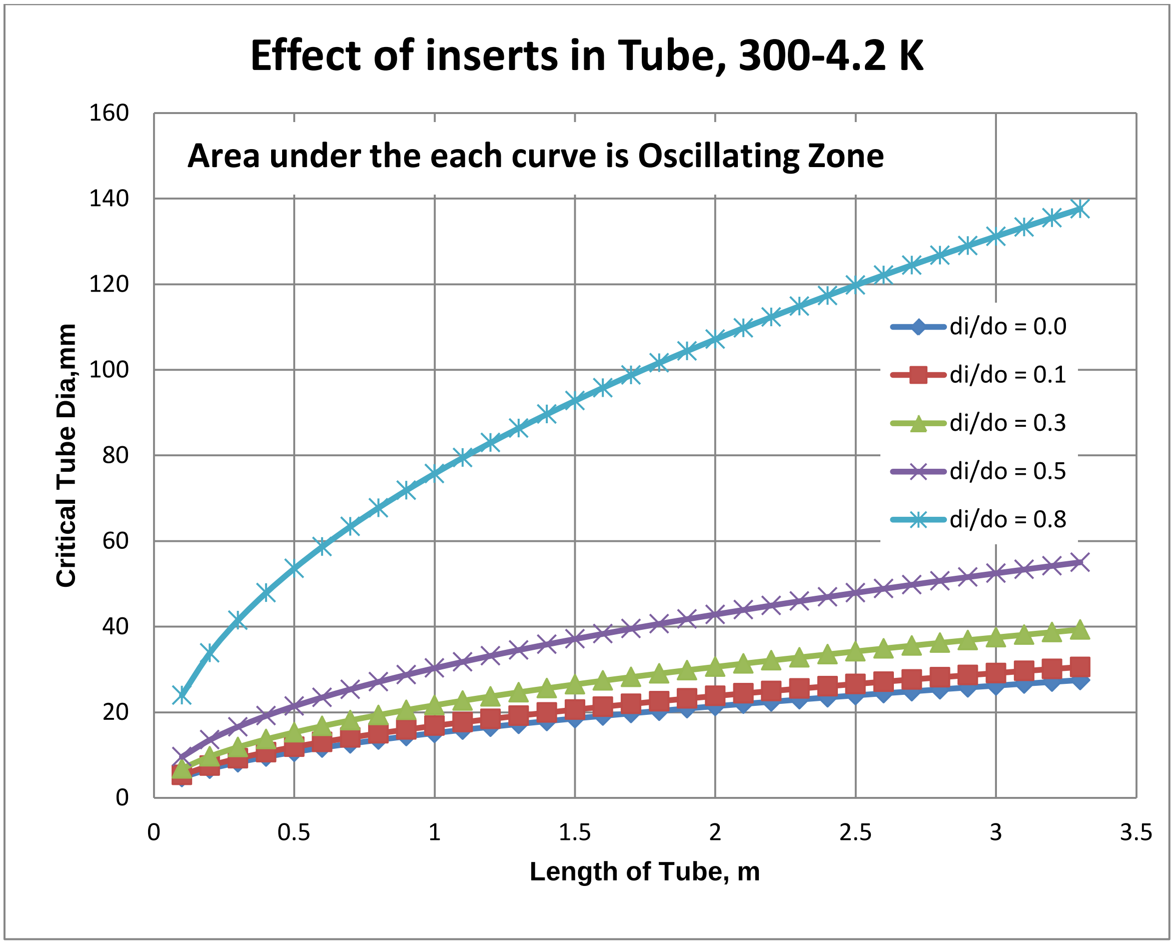

Figure 5: Length-diameter combinations in the presence of inserts for the temperature boundary conditions of 300 K and 4.2 K

Similarly, Figure 6 presents the selection criteria for a tube of which one end is 80 K and another end is maintained at 4.2 K.

The analysis also studied the most appropriate location of an 80 K intercept to dampen the thermo-acoustic oscillations in the tube without inserts. It is assumed the warm end is at 300 K and the cold end is at 4.2 K. For a given tubing length and inner diameter, the minimum distance from 300 K to the 80 K intercept (and therefore the maximum distance from the 80 K intercept to 4.2 K) for oscillation-free operation is calculated by the stability limit Y_c = 100. This satiability limit has been calculated from Equation 2 for the fixed temperature ratio α = 19.05 ($\alpha = \frac{T_H}{T_L} = \frac{80}{4.2}$). This stability limit is the limiting factor to determine the most appropriate location of an 80 K intercept between the hot end (300 K) and the cold end (4.2 K).

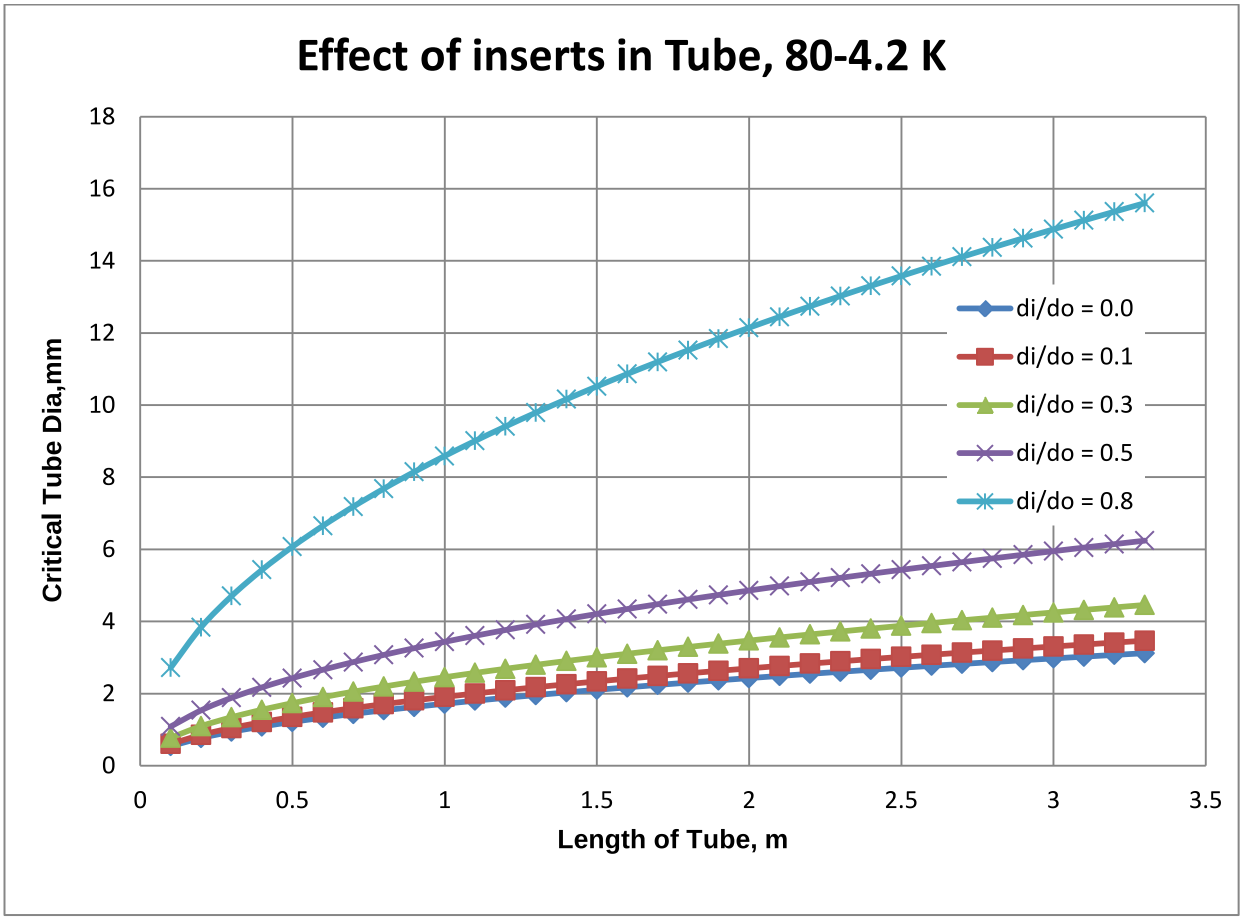

Figure 6: Length-diameter combinations in the presence of inserts for the temperature boundary conditions of 80 K and 4.2 K

Results of this analysis are shown in Figure 7. This analysis reveals some interesting facts. Figure 7 shows that there is a minimum distance for certain inner diameters of tubes. For a 5 m long tube, the minimum distance from the 300 K end to the 80 K intercept is 3 m for a 2.5 mm inner diameter and 2 m for a 3.0 mm inner diameter. If the tube inner diameter is 4.8 mm or greater, the 80 K intercept could be placed at any position.

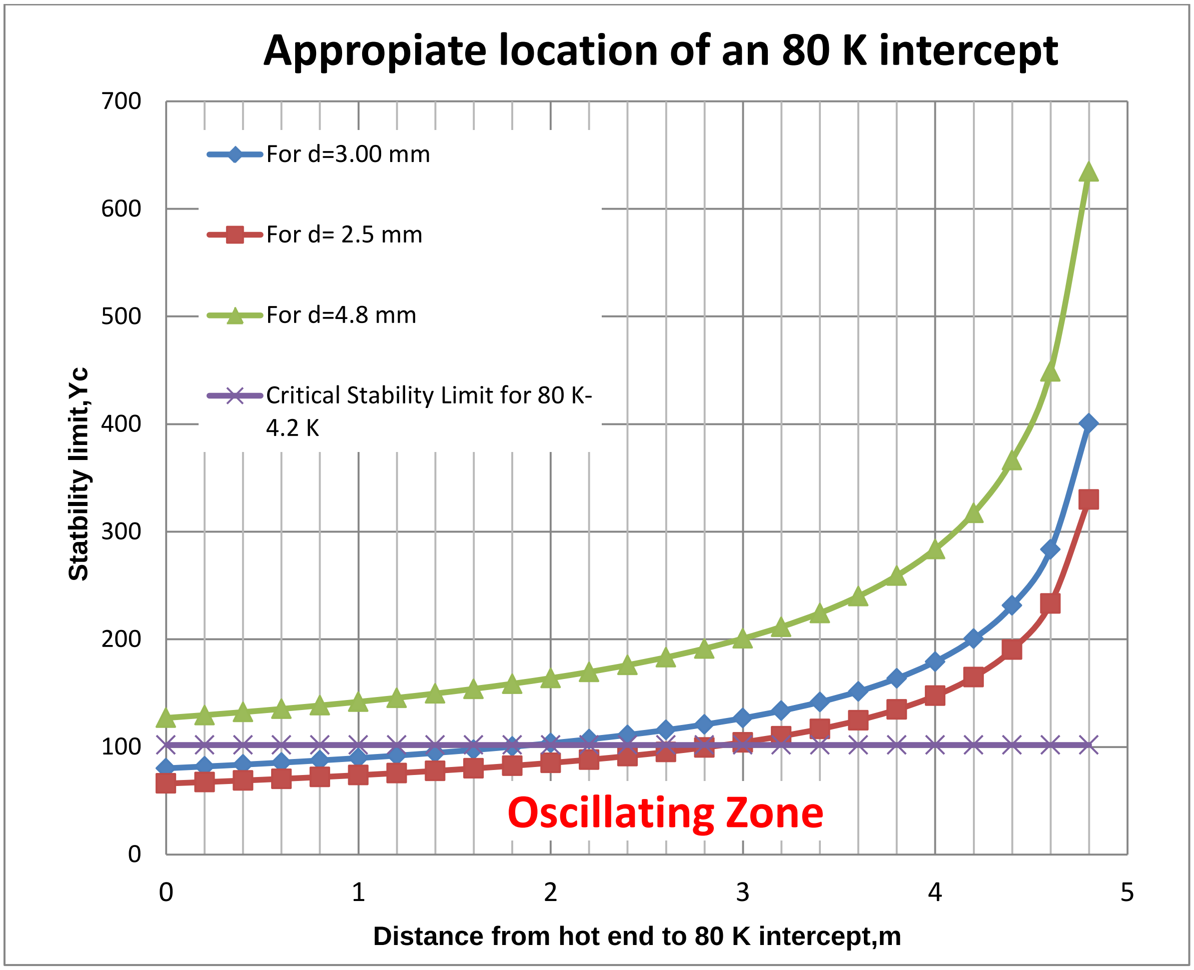

Figure 7: Stability-limited minimum distance of 80 K intercepts from the 300 K end to avoid thermo-acoustic oscillations.

4. Conclusions

This analysis presents a simple method to size helium tubes that will be free of thermo-acoustic oscillations. The presented figures can serve as a reference for determining the oscillating and non-oscillating zones for different tube length-diameter combinations.

Design guidelines can also be obtained for sizing oscillation-free helium tubes when inserts are used. The presented analysis also provides useful information for an appropriate location of an 80 K intercept to avoid thermo-acoustic oscillations. This analysis is based on the lower stability curve of Rott's analysis.

Acknowledgments:

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