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J. D. Fuerst

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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AN INVESTIGATION OF THERMALLY DRIVEN ACOUSTICAL OSCILLATIONS IN HELIUM SYSTEMS

J.D. Fuerst

Fermi National Accelerator Laboratory*
Batavia, Illinois USA

Abstract

The phenomenon of thermal-acoustic oscillation is seen to arise spontaneously in gas columns subjected to steep temperature gradients, particularly in tubes connecting liquid helium reservoirs with the ambient environment. This is often the arrangement for installed cryogenic instrumentation and is accompanied by undesirably large heat transfer rates to the cold region. Experimental data are collected and matched to theoretical predictions of oscillatory behavior; these results are in good agreement with the analytical model and with previously collected data. The present experiment places the open ends of oscillating tubes of various lengths and cross sections in communication with flowing helium in the subcooled, 2-phase, or superheated state while the other ends are maintained at some controlled, elevated temperature. Assorted cold end conditions are achieved through adjustments to the Fermilab Tevatron satellite test refrigerator to which the test cryostat is connected. The warm, closed ends of the tubes are maintained by isothermal baths of liquid nitrogen, ice water, and boiling water. The method is contrasted to previous arrangements whereby tubes are run from room temperature into or adjacent to a stagnant pool of liquid helium. Additionally, the effect of pulsations in the flowing helium stream is explored through operation of the refrigerator's wet and dry expanders during data collection. These data confirm the theory to which they were compared and support its use in the design of cryogenic sensing lines for avoidance of thermoacoustic oscillation.

Introduction

Under certain conditions columns of gas may be induced to oscillate in an undamped manner. Typically this behavior occurs within a length of tube, either open at both ends or closed at one end and with frequencies associated with acoustic phenomena. The former case establishes what is known as the Rijke oscillation, where heat added to a grid placed in the lower half of a vertical pipe drives thermoacoustic oscillations when gas flows up through the pipe. Details concerning this effect are supplied by Feldman [1]. The latter case prescribes the Sondhauss effect (after Sondhauss, who in 1850 conducted tests with heated glass tubes [2]), where heat added to the closed end of a pipe causes gas in the pipe to oscillate. In the world of cryogenics this effect is often known as Taconis oscillation, after K.W. Taconis who witnessed and described the phenomenon during experiments with solutions of ^{3}He in ^{4}He in 1949 [3]. The generic term "thermoacoustic oscillation" is also used in cryogenics to describe this behavior, as it primarily occurs in liquid helium systems where tubes open to the liquid helium environment extend outside the insulation system and expose their closed ends to the ambient. Chief among the problems associated with this behavior is the enormous increase in heat flux from warm end to cold end which can be 1000 times as great as that explained by conduction down the tube itself [4]. Many references are available detailing the history of the phenomenon [1,2,3,4,5,6,7].

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Kramers undertook the first mathematical exploration of the stability curve for thermoacoustic oscillations in his paper of 1949 [8]; results were in poor agreement with the experimental evidence of the day. This work was extended by Nikolaus Rott in a 1969 paper [5], resulting in a successful theoretical model mapping out with selected dimensionless parameters a stability curve within which oscillations are predicted and external to which oscillations are nonexistant. Parameters include the temperature ratio (warm end/cold end), length ratio (warm length/cold length, each assumed constant and separated by a discontinuous jump), and ratio of tube diameter to Stokes boundary layer thickness. Numerical calculations are performed later by Rott in [9] which completely map out this curve. It is discovered that there are in fact two branches of the curve: a lower branch where the boundary layer thickness is large relative the the tube diameter (obeying the "fully viscous" assumption) and an upper branch where the boundary layer thickness is large at the cold end but small (normal boundary layer approximations) at the warm end [9]. It turns out that most of the upper branch is inaccessible in practice because the temperature ratios are excessively high.

Conclusions supplied by Rott in [9] state that from an oscillation production standpoint, the optimum position of the jump in temperature is at the center of the half-open tube and little effect is seen for increases in length ratios up to 2:1. Also, he predicts the minimum temperature ratio capable of supporting oscillations to be about six. This value was verified by Hoffman, Lienert, and Quack [10] and by the present investigation. Rott determined that the failure of the Kramers theory lies in the nature of helium's thermophysical properties. While Kramers' theory produced asymptotes of the stability curve, they lie at virtually infinite temperature ratios for helium (see reference [9] for a more complete discussion). Using Rott's theory, one sees that in addition to altering the geometry of the oscillating system to eliminate oscillations, one can either heat or cool the closed end to reach stable portions of the stability curve. Following Haycock [2], it is seen that heating the closed end will increase the kinematic viscosity and control acoustic damping while cooling the closed end decreases the thermal potential below that capable of sustaining oscillations - the lower branch of the curve is reached.

Theoretical treatments of similar problems include Liburdy's analysis of an annular half-open tube [11], modeling the fact that often times thermoacoustical oscillations may be damped by inserting a small rod into the oscillating line. The analysis follows Rott closely. This work shows that stability is increased by a decrease in annular gap; this is effected by a significant upward adjustment in the lower branch of the stability curve and a somewhat more modest downward shift in the upper branch. Additional work by Liburdy [12] investigates the stability question for laminar steady flow of cryogens. The analysis proceeds in similar fashion to that of the half-open tube case. The effects of flow are shown to reduce the instability envelope by shifting the upper branch downward as flowrate increases. Not much change in the lower branch is recorded.

Experimental Analysis

Recently, experimental work has centered around quantitative verification of the theories of Rott. For example, Gorbachev, et al [13] used a 4 millimeter inner diameter tube with the open end at 4.2K and the closed end at ambient conditions to take data. Warm and cold lengths of tube were altered by adding coils at the respective locations. For these data, "warm" is defined as T>150K while "cold" means T<150K. Hoffman, Lienert, and Quack [10] took data specifically designed to verify the Rott stability curve; results were qualitatively correct but shifted. Yazaki et al [14] also experimentally verified the Rott curve but used a slightly different technique. Instead of using a half-open tube, the oscillator consisted of a U-shaped tube with both open ends at ambient and the bend in the "U" existing at the midpoint and located at the cold region, providing great flexibility in selection of operating conditions.

The current apparatus makes use of a warm isothermal bath and helium bleed flow to enforce the assumption in the Rott theory of constant warm and cold temperatures separated by a discontinuity as shown in Figure 1. Thermometry is provided at appropriate locations to verify these conditions. Tests are conducted using half-open tubes, with a diaphragm-type pressure transducer mounted at the warm end such that minimal additional warm volume extraneous to the tube is created. Helium is contained in a flowing line contiguous with the refrigeration system. The system used is one of many satellite refrigerators operated in support of the Tevatron superconducting dipole array at Fermi

National Accelerator Laboratory [15]. The refrigerator provides a nominal 600 watts of refrigeration capacity at 4.5K with about one gram per second of 4.5K liquefier load. Adjustment of the refrigerator operating conditions allows data to be taken at a variety of cold end temperatures and pressures. Tubes of three different diameters are tested, with modifications to the length ratios accomplished by adding lengths of warm tubing. A map of the stability curve is generated by varying tube diameter, tube length ratio, and fluid flow parameters (see results next section). Also, the effects of pulsations in the cold helium stream were evaluated by operating the refrigerator's reciprocating expansion engines during data collection [16]. The oscillating sensor tubes are of 3.18 mm O.D, 6.35 mm O.D, and 12.7 mm O.D., all with 0.89 mm wall thickness. Cold lengths are about 500 mm.

Results

By varying the pressure and temperature in the flowing line through the test cryostat, a map of the stability/instability region was generated. A major disappointment was the inability to verify both branches of the stability curve, as done by Hoffman et al. This would require use of a higher temperature warm bath and may be attempted in the future. Oscillations were clearly defined and there was rarely doubt as to their presence or absence. Operation of the test refrigerator was smooth enough to allow extended periods of steady state, during which measurements were taken. Three graphs of the stability curve were produced, each with a different length ratio (0.3, 1.0, 2.0). These graphs are shown in figures 2, 3, and 4. Superimposed on the data are the theoretical predictions of Rott for each case (solid lines). To fix nomenclature, ς = length ratio (warm to cold), α = temperature ratio (warm to cold), and Δ = ratio of tube diameter to Stokes boundary layer thickness = $(d_o/2)[a_c/(l_c \nu_c)]^{1/2}$ where d_o = tube I.D., A_c = sound speed of gas at T_{cold}, ν_c = kinematic viscosity at T_{cold}, and l_c = cold length.

Specific to the $\varsigma = 0.3$ graph Figure 2, one sees some agreement between the theoretical prediction of the stability curve and the data. Without the ability to precisely control fluid properties (see Yazaki, et al), an exact demarcation between oscillating and non-oscillating regions is difficult to produce. Rather, the author has attempted to generate enough data to evenly cover the field with closely spaced data points, allowing the border between oscillation and non-oscillation to manifest itself. As the graph demonstrates, it is possible to state that at least qualitatively, the Rott theory is correct for $\varsigma = 0.3$. Oscillation frequencies varied between 25 and 125 Hz. The $\varsigma = 1.0$ graph Figure 3, contains many more data points and hence ought better to define the stability curve. However, much of the data is clumped together around certain more readily accessible parameter values. Nevertheless, agreement between the data and the Rott theory for ς = 1.0 is better than the $\varsigma = 0.3$ case. Frequencies were in the 16 to 100 Hz range, with the majority of the data oscillating at about 25 Hz. Finally, the $\varsigma = 2.0$ graph Figure 4, shows the best (albeit still clumpy) distribution of data and comes closest to defining the inner portion of the stability curve. Frequencies ranged in the 12 to 90 Hz range, with most points showing frequencies of about 17 Hz. All three graphs show pronounced intermingling of the oscillation/no oscillation points in the upper right corners of the plots. Data in this region all share the characteristics of high temperature ratio and high Δ. This combination is created almost exclusively in the 12.7 mm dia. tube due to the role of diameter in Δ. It is possible that thermoacoustic oscillations are less likely in tubes of relatively large I.D.; data from other sources do not contain sensing lines as large as the largest used in this experiment.

No particular effects were recorded in view of the fact that the low temperature end of the sensing tubes was maintained via a flowing helium stream rather than a stagnant pool - the results are in reasonable agreement with experiments done using the latter method. Operation of the refrigerator's expansion engine superimposed a low frequency "jump" corresponding to engine speed (2-6 Hz) on the sensing lines' pressure traces. Oscillations of thermoacoustic frequencies were never observed to initiate or dissipate with the commencement or cessation of engine operation. However, on rare occasions, oscillations were seen to arise in an otherwise steady state situation when a check valve in the refrigerator distribution piping began to chatter. Rough estimates of chatter frequency correspond to thermoacoustic frequencies. The conditions under which these oscillations were induced generally did not fall inside the stability boundary (the oscillating region). When the check valve ceased to chatter, the oscillations disappeared. It is possible to conclude that oscillations may be induced in a sensing line by introducing pressure fluctuations of suitable frequency at the cold end even if conditions point to a stable configuration on the Rott stability curve. This feature is worth further investigation.

Conclusions

Thermoacoustic oscillations interfere with the efficient operation of a cryogenic helium system, potentially increasing the system heat leak by a factor of 1000. Unless the phenomenon is understood, the likelihood of suffering these effects in a cryogenic system is high due to the almost universal requirement for instrumentation lines (pressure, temperature, flow, etc.) which must run from the cold regions of the system (where they are open to the process) out to the ambient (where they are connected to transducers, etc.). The best theory explaining and predicting the occurrence of thermoacoustical oscillation is that of Nikolaus Rott. This theory describes the phenomenon in terms of a "stability curve" defined by the dimensionless parameters ς, α, and Δ. For a given geometry, cold end condition, and ambient temperature, it is possible to predict whether or not oscillations will occur. Looked at from the other direction, one can use the Rott stability curve to design instrumentation lines that will not oscillate for given ambient temperatures and cold end conditions.

Results confirm the lower branch of the Rott stability curve as well as the nose of the curve. Unfortunately, no data was produced to pin down the upper branch of the curve. More effort is required in this area. Low frequency pulsations in the flowing helium stream were seen to have no effect on the presence or absence of oscillations; rather, the oscillation (or lack thereof) merely "rode" the lower frequency pulsations. However, oscillations were induced by the onset of chatter in a check valve somewhere in the system (of frequencies similar to thermoacoustic). These oscillations vanished when the chatter quit. The possibility of such an event must be taken into account when designing cryogenic sensing lines. Finally, oscillation in lines of relatively large diameter is less predictable, perhaps playing a less dominant role in the system behavior compared to other effects such as convection.

Acknowledgements

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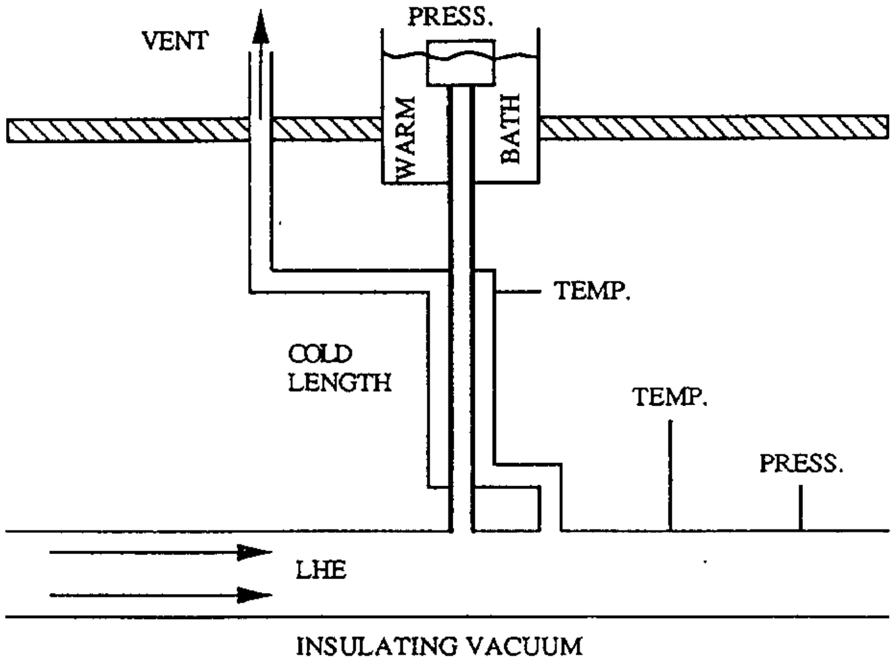

Figure 1: Experimental Apparatus

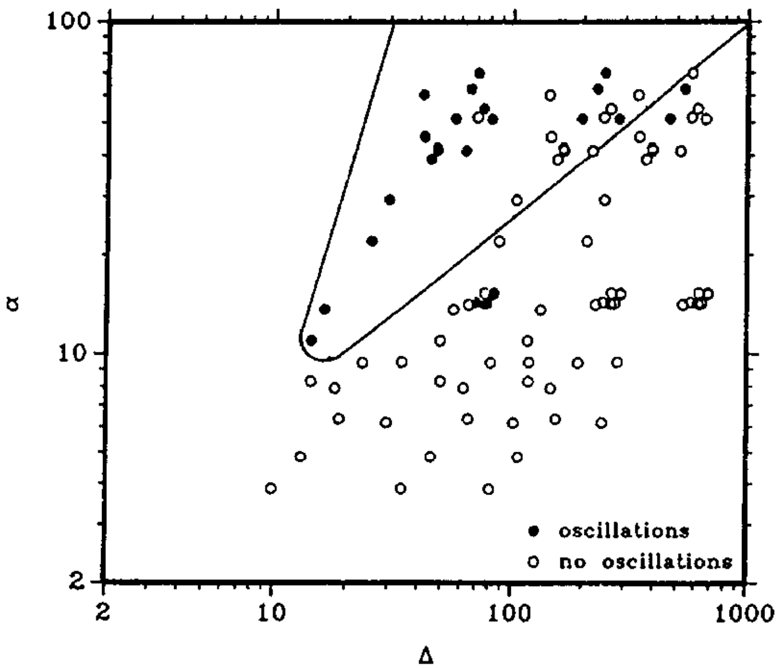

Figure 2: Data for length ratio $\varsigma = 0.3$

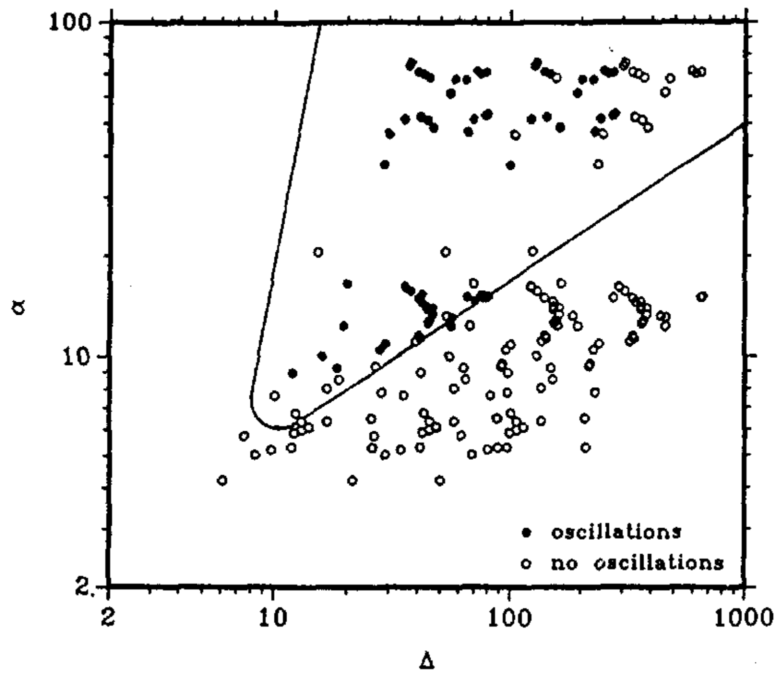

Figure 3: Data for length ratio $\varsigma = 1.0$

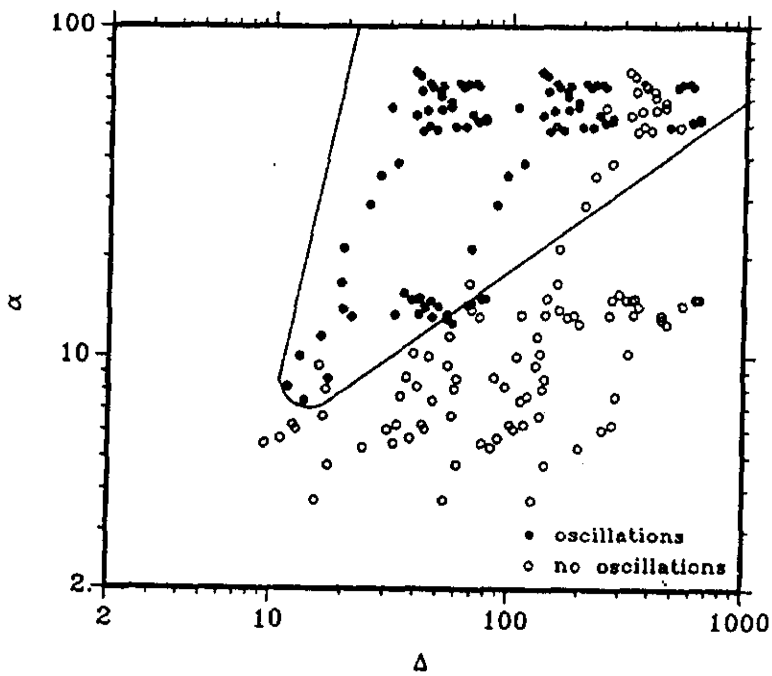

Figure 4: Data for length ratio $\varsigma = 2.0$