PREDICTION OF THERMAL ACOUSTIC OSCILLATIONS (TAOs) IN THE CLAES SOLID CO_2/NEON SYSTEM

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ABSTRACT

A study was initiated to investigate the possibility that the existence of TAOs in the Cryogenic Limb Atmospheric Etalon Spectrometer (CLAES) neon plumbing system ground configuration could be the cause of higher-than-predicted heat rates measured during thermal ground testing. This study consisted of both analysis and a series of lab tests which were performed using Lockheed's Small Insulation Test Calorimeter (SITC) filled with solid neon. The tests were conducted between warm boundary temperatures ranging from 40 K to 100 K which simulated the actual test conditions of the CLAES CO_2/neon system. TAOs were observed between 6 and 106 Torr which agreed with the analytical predictions and verified the possible existence of TAOs in the CLAES system during ground testing. The presence of TAOs was eventually confirmed in the CLAES system during a subsequent thermal test and were determined to have caused the higher heat rates measured during the prior thermal test. It was also confirmed through analysis and testing that the TAOs would not be present during orbital conditions and thus not affect the CLAES lifetime.

INTRODUCTION

The Cryogenic Limb Atmospheric Etalon Spectrometer (CLAES) is one of several scientific instruments that will be examining the Earth's atmosphere on the Upper Atmospheric Research Satellite (UARS). The satellite is scheduled to be launched on the Space Shuttle Discovery in October of 1991. The CLAES system is comprised of two main components, the etalon spectrometer telescope with its associated optics and the two-stage solid CO_2/neon cooler. The solid neon provides the primary cooling of the spectrometer's focal plane and the CO_2 thermally guards the solid neon and provides cooling of the spectrometer's optics.

The predicted on-orbit lifetime of the CLAES cooler is 25 months which was determined using Lockheed's thermal analyzer program, THERM. Thermal ground testing of the cooler is done to validate the thermal model. It was during the initial thermal ground test of the CLAES system that a higher-than-predicted heat rate to the solid neon was measured. After initial investigations comparing the ground test data to the thermal model predictions did not provide any likely source of the higher heat rate, it was concluded that Thermal Acoustic Oscillations (TAOs) possibly existed in the CLAES neon plumbing system ground configuration. A study was initiated to investigate this possibility.

TAO BACKGROUND

TAOs occur in cryogenic systems where a long tube open at the cold end is extended to the closed end at the warm boundary. This usually happens in the fill line or the ground-hold vent line where the tube is usually capped off (at the hot end) when the cryogenic dewar is in orbit. TAOs can be very damaging, as the oscillations are accompanied by a considerable heat conduction down the tube. This can increase the heat leak of the system by several orders of magnitude, thus decreasing the useful on orbit lifetime of the cryogenic system.

The TAO phenomenon was known as early as 1804[1]. Rayleigh[2] provided an explanation for the heat-driven oscillation based on a critical value now known as the Rayleigh's number. Keesom[3] also mentioned the effect of TAOs in 1942. Taconis[4] has offered a qualitative explanation of these oscillations. In 1949, Krammers[5] attempted to use sound theory to provide a quantitative description of phenomenon. He concluded that no useful results can be derived from the linear stability theory, due to the neglect of nonlinear terms. Twenty years later, Rott[6-8] showed that it was only for the special combinations of the material constants of helium gas that Krammers had failed. Using a second order (in viscous effect) but still linear theory, Rott was able to derive the stability curve for helium gas in a long tube with piecewise step change of temperature. For temperature profiles other than a step function, NIST[9] has developed a computer program based on Rott's analysis.

TAO INVESTIGATION

As for TAOs in gases other than helium, no stability curves were available until recently. Gu and Timmerhaus[10,11] derived the stability criterion for triple point hydrogen. For the present case of a neon system, the stability limit is not known. According to the second order - linear theory, three properties of the working gas are most important in determining the stability criterion. They are the Prandtl number, the ratio of heat capacity $\gamma = c_p/c_v$ and the exponent of temperature power law for viscosity, β. The heat capacity ratio for an ideal monatomic gas (both He and Ne) is

$$\gamma = c_p/c_v = 5/3 \tag{1}$$

It can be shown that the Prandtl number can be expressed as follows[12]

$$\mathrm{Pr} = \frac{\eta c_p}{k} = \frac{\gamma}{1.77\gamma - 0.45} \tag{2}$$

and the Prandtl number is seen to be a constant. For a monatomic gas one can substitute Equation (1) into (2) and get Pr=0.667. The above definitions assume an ideal gas, which is quite applicable for the temperature and pressure ranges for TAOs. The remaining property is the exponent of the power law for viscosity (η).

$$\eta = aT^{1+\beta} \tag{3}$$

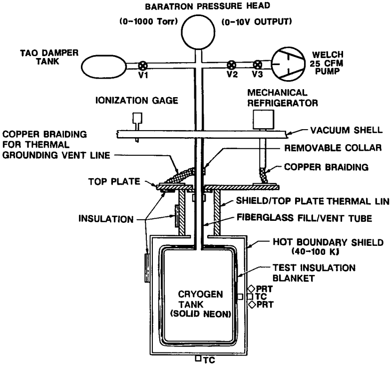

Figure 1 SITC Neon TAO Test Configuration Schematic

For helium gas below 273 K, β=0.647[13] and above 273 K, β=0.661. From 33 K to 1073 K, β=0.6567 has been proposed. On the other hand, for neon, β=0.661. Since all three properties are very close for both He and Ne, one can conclude that the stability curves derived for helium gas should be applicable to neon gas also.

In order to determine whether TAOs exist in the CLAES neon plumbing system, a test was set up using Lockheed's Small Insulation Test Calorimeter (SITC) which is shown schematically in Figure 1. The system consists of a cryogen calorimeter tank that usually supports a test insulation blanket. A hot boundary shield completely surrounds the calorimeter tank to provide thermal guarding and establish boundary conditions. Both the shield and tank are supported from a room temperature vacuum shell by a single 1-cm-diameter fiberglass fill/vent tube that has a 0.5-mil stainless steel foil coating to prevent gas permeation. The hot boundary shield is cooled using a mechanical refrigerator. A Lakeshore Cryotronics temperature controller is used to control the shield temperature through heaters and PRTs that are mounted to the shield.

In the CLAES system, various plumbing line sizes and lengths exist between different temperature conditions due to thermal grounding. In order to investigate whether the existence of TAOs was possible in the least amount of time, it was determined to bracket the various range of temperature conditions by controlling the shield in the SITC to 40 K and 100 K. Figure 2 shows the temperature profile of the fill/vent line for the SITC being tested, with shield temperatures of 40 K and 100 K respectively. In order to use Rott's stability curves, a piecewise step function for the temperature along the vent line has to be assumed. This is represented by the solid line in Figure 2 (for the 40 K shield temperature).

The TAOs stability curves for neon (or helium) are plotted in Figure 3. The Y-axis represents the temperature ratio of the warm to the cold boundary $\alpha=T_H/T_C$. The X-axis consists of a dimensionless parameter (Δ) which is a function of the speed of sound (C) and kinematic viscosity (υ_C) of the cold gas, and the cold tube length (l_C). TAO predictions based on the piecewise temperature step function shown in Figure 2 for the SITC test configuration were made and are shown in Figure 3. TAOs were predicted to exist between 3-4 Torr and 100 Torr for a 40 K shield and range in frequency from 33 to 40 Hz. For a 100 K shield, the predicted pressure range was between 10 and 50 Torr.

In order to use the SITC to perform the test, the external fill/vent system was modified by adding a TAO damper tank, three valves (V1, V2, and V3), a Welch 25 cfm pump and a 1-1000 Torr Baratron pressure head. The configuration is shown in Figure 1. Valve V1 was used to isolate the TAO damper tank from the neon vent. Valve V3 was a full open/full closed valve that was used to isolate the Welch pump from the neon vent. Valve V2 was used as a metering valve to control the neon vapor pressure by limiting the vent rate through the pump.

The sensitivity of the Baratron pressure head was measured prior to installation into the SITC using a pulse tube bellows compressor with bypass to produce sinusoidal pressure pulses and a Tektronix oscilloscope to monitor the output. Pressure frequencies ranging from 2 to 35.5 Hz were measured by changing the speed of the compressor. The maximum measured frequency was compressor limited. By using the compressor's bypass valve, pressure amplitudes were decreased and measured down to .2 Torr.

Liquid neon was transferred to the calorimeter tank inside the SITC and the Welch pump was used to solidify the neon through valves V2 and V3. Valve V1 was closed and isolated the TAO damper from the neon gas. The hot boundary shield was cooled and controlled to 40 K for the initial

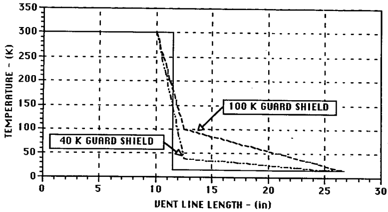

Figure 2 SITC Assumed Fill/Vent Line Step Temperature Change

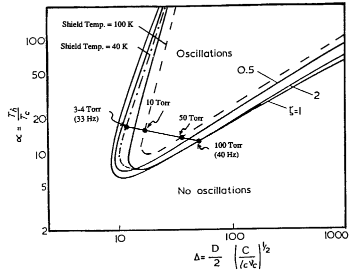

Figure 3 Neon Stability Curves Applied to the SITC Test Configuration

test. The vapor pressure was varied using valve V2 to throttle the pump. V2 was closed periodically during the initial pump down to check for TAO presence. Using this technique, TAO's were observed to start appearing at 106 Torr. Opening V1 to the TAO damper tank resulted in no observable oscillations. Pumping continued down to 6 Torr where the TAOs were observed to dampen out. The measured TAO frequency ranged from 29 to 36 Hz and varied in peak-to-peak amplitude from .2 to 2.8 Torr.

At a pressure of 25 Torr, the system was completely sealed off by closing V1, V2 and V3 to determine the rate of rise of the neon vapor pressure which directly translates in the temperature rise rate of the solid neon and the amount of energy the neon is absorbing. During this configuration, the presence of TAOs was verified and the pressure rise rate was .82 torr/hr. Opening V1 dampened the oscillations and decreased the pressure rise rate decreased to .16 torr/hr. Therefore, it was concluded that the presence of TAOs in this configuration increased the nominal (no TAO) heat rate to the solid neon by approximately five times.

After the hold test, the neon vapor pressure was increased to above 110 Torr and the shield temperature changed to 100 K. The test was repeated at this temperature and it was determined that oscillations began at 65 Torr and dampened out at 9 Torr. Opening valve V1 during any time during this test dampened out the oscillations. The TAO frequencies ranged from 31 to 39 Hz with peak-to-peak amplitudes from .4 to 4.8 Torr.

On several occasions, at pressures above 29 Hz, TAOs were observed to be initially present but dampen out on their own after approximately fifteen minutes. Figure 4 shows a typical self-extinguishing TAO profile at 37 Torr. One possible explanation for the self-extinguishing could be that the presence of the TAOs in the vent line causes higher heat loads to be transmitted to the fiberglass fill/vent line and sufficiently changes the temperature profile of the line until their presence was no longer possible. This would tend to indicate a possible cycling "on/off" oscillation that would start again once the temperature profile of the tube reestablished itself.

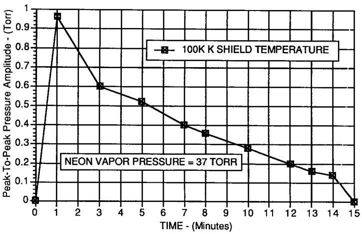

Figure 4 Neon TAO Self-Extinguishing Profile

CONCLUSIONS

TAOs were observed in the SITC neon test configuration and the results agreed well with analytical predictions based on the stability curves derived for helium gas which were also found to apply to neon gas. A comparison of the results to prediction is shown in Table 1. The presence of TAOs was shown to increase the neon pressure rise, thus the nominal heat rate, in the SITC configuration by approximately five times.

The analysis and test verified the possible existence of TAOs in the CLAES neon plumbing system during ground testing. The presence of TAOs was eventually confirmed in the CLAES fill/vent line during a subsequent thermal ground test[14] in which Baratron pressure heads similar to the one used in the lab test were incorporated into the CLAES external plumbing manifolds. The TAOS were observed to start forming at 21 Torr and found to dampen out below 1 Torr (16.0 K to 19.5 K) which agreed well with predictions. This pressure was lower than was obtained during the initial thermal test due to the use of a Roots blower to provide additional pumping capacity. The subsequent thermal ground test yielded measured neon heat rates that agreed well with thermal model predictions. The 1 Torr (16.0 K) is higher than the on orbit operating condition (13.8 K), thus TAOs would not be present during orbital conditions and therefore, not affect the CLAES lifetime.

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Table 1 Analytical Prediction and Test Result Comparison

	40 K SHIELD				100 K SHIELD			
	PRESSURE		FREQUENCY		PRESSURE		FREQUENCY	
	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
PREDICTION	3-4 Torr	100 Torr	33 Hz	40 Hz	10 Torr	50 Torr	>33 Hz	<40 Hz
MEASUREMENT	6 Torr	106 Torr	29 Hz	36 Hz	9 Torr	65 Torr	31 Hz	39 Hz

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