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Study of thermoacoustic oscillations in half-open tubes for saturated superfluid helium

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Abstract

Thermoacoustic oscillations (TAOs) are spontaneous pressure oscillations frequently seen in hydrogen or helium cryogenic systems. Half-open tubes connected to cryogenic fluid with a closed room temperature end have a high potential for oscillation generation. Thermoacoustic oscillations will result in significant pressure fluctuations and additional heat load, endangering the security and stability of the cryogenic system. The goal of this paper is to investigate TAOs in superfluid helium using both theoretical and experimental methods. Five half-open tubes with varied typical inner diameters inserted into superfluid helium were installed in a test cryostat. The onset characteristics of thermoacoustic oscillations were presented and studied. The effect of temperature profile was discussed. Finally, a simple eliminating method was introduced.

Keywords: cryogenic system, thermoacoustic oscillations, saturated superfluid helium, onset characteristics

1. INTRODUCTION

Thermoacoustic oscillations (TAOs), first detected by K. W. Taconis in 1949, are often observed in hydrogen or helium cryogenic systems. This phenomenon usually occurs in half-open tubes which connect cryogenic fluid with room temperature end. As shown in Fig. 1, cryogenic fluid moves to the warm end of these tubes, absorbs heat, and then pressurizes and drives back down to the cold end. If certain conditions are met, such as an appropriate warm to cold temperature ratio, working pressure, and geometric structure, self-sustaining pressure oscillations may be stimulated.

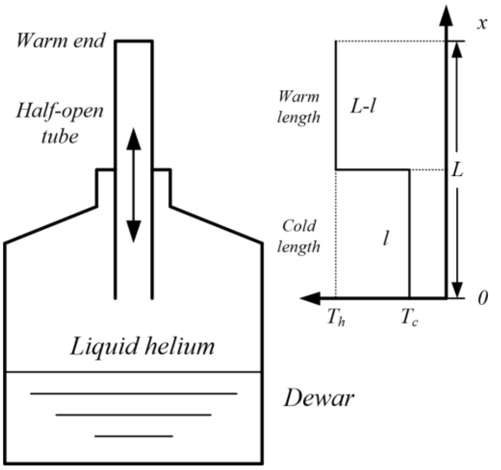

Fig. 1. Diagram of thermoacoustic oscillation in a half-open tube.

Taconis oscillations introduce an extra cryogenic heat load that is significantly greater than the pure thermal conduction of the tube [1] and is always harmful to the cryogenic system [2]. Following Taconis' discovery of this phenomenon, much theoretical and experimental work has been done to determine whether TAOs could appear under certain conditions. Rott proposed the frequency-domain linear thermoacoustic theory in 1969 [3, 4]. He obtained stability curves for three parameters: warm to cold temperature ratio α, warm length to cold length ratio ξ, and the ratio of tube diameter to Stokes boundary layer thickness Y. The stability curves for helium are shown in Fig. 2 [4]. For various parameters, the lower and upper branches envelop the oscillation zone. The other area will be oscillation free. Following Rott, Gorbachev [5], Fuerst [1], Yazaki [6], and others [7-10] conducted their research independently. They all concluded that TAOs could be predicted by linear theory with reasonable accuracy.

In recent years, saturated superfluid helium has become the most significant coolant for large superconducting accelerators, such as SHINE (Shanghai high repetition rate XFEL and extreme light facility), CiADS (China initiative Accelerator Driven Subcritical System), HIAF (High Intensity heavy ion Accelerator Facility), ESS (European Spallation Source) and Linear Coherent Light Source (LCLS-II). Cryogenic systems with a cooling capacity of more than 2 kW at 2 K temperature have been used in these facilities. However, thermoacoustic oscillations in saturated superfluid helium for half-open tubes have rarely been studied. The warm-to-cold temperature ratio is relatively high and the applicability of linear theory should be verified. The primary objectives of this research are: (1) Forecasting TAOs of half-open tubes for saturated

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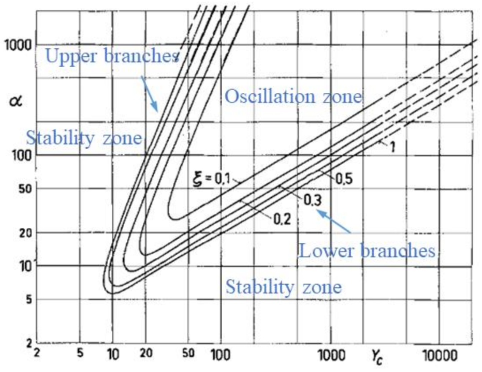
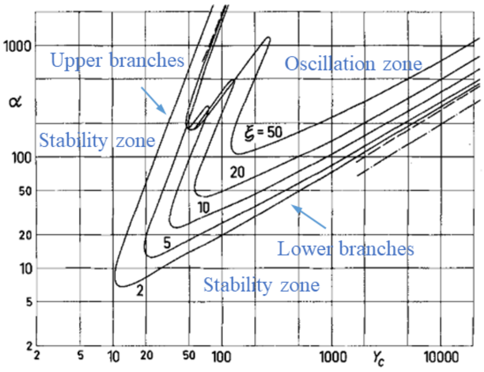


(a) 0<ξ≤1



(b) 1 < ξ<∞

Fig. 2. Stability curves for helium

superfluid helium with linear theory, which has received little attention in the past. (2) Characterizing TAOs of saturated superfluid helium by experiments.

2. STABILITY ANALYSIS

As shown in Fig.1, the tube is filled with helium gas at 3129 Pa (saturated pressure at 2.0 K). The cold end temperature is 2 K (T_c) and the warm end temperature is 300 K (T_h). The temperature ratio is 150($\alpha = T_h / T_c$). Rott's assumption used a step temperature profile along the tube, suggesting a temperature jump in the tube. The tube is open at the cold temperature, and the temperature can rise to the hot end temperature. the cold length is l and the length ratio is $\xi = (L-l)/l$ .As illustrated in Fig. 2, the temperature jump that occurs at the center of the tube (ξ=1) will result in the largest interval. For given working conditions, Y_c lies between two values for oscillation cases.

The quantity Y_c was defined as

$$Y_c = r_0 \left[\frac{a_c}{l v_c} \right]^{\frac{1}{2}} \qquad (1)$$

Where a_c is the sound speed at cold temperature, v_c is the kinematic viscosity at cold temperature ,and r is the inner radius.

The value of λ_c is given by

$$\lambda_c = \frac{\omega l}{a_c} = \frac{2\pi f l}{a_c} \qquad (2)$$

Where ω is the angular frequency, f is the frequency.

The sound speed at cold temperature (a_c), the kinematic viscosity at cold temperature (v_c), and the length ratio are exact values for given working conditions. So, there are two critical inner radii (r) for a tube with a length of L = 1.0 m, ξ = 1, and a temperature ratio of 150. Y_c is between 20 and 2000. As illustrated by Rott, λ_{c1} = 1.43 is for the small value of Y_c, and λ_{c2} = 0.85 for the enormous value. The upper branch's corresponding critical radius (r_1) is 1.27 mm, whereas the lower branch (r_2) is 127 mm. It means that a 1.0 m long half-open tube inserted into saturated superfluid helium with an inner radius between these two values has the opportunity to produce TAOs. It should be noted that Rott's simplifications assume that the tube radius r_0 is substantially smaller than the tube length L, implying that the lower branch radius estimated will have some errors when the tube diameter is large enough. The corresponding frequencies are 35.8 Hz and 21.7 Hz.

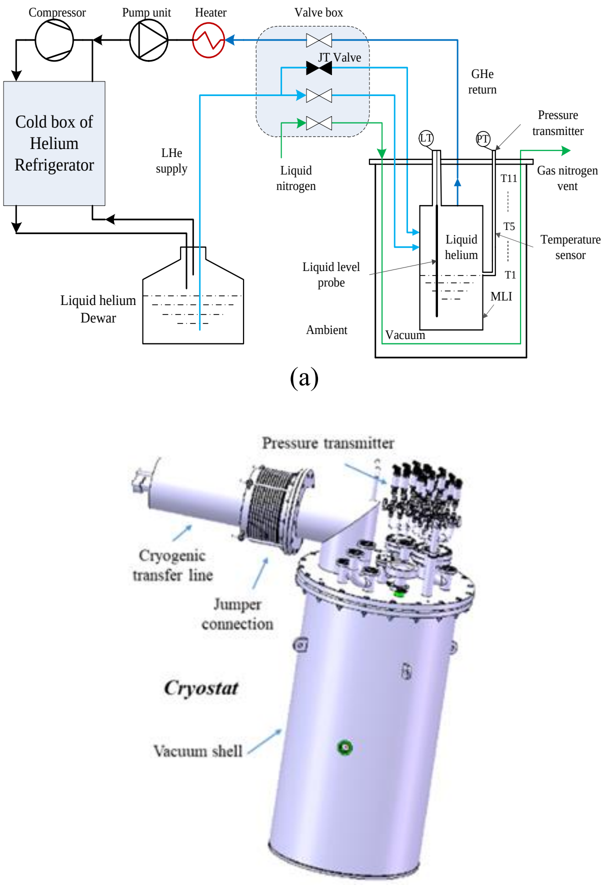
In a practical superfluid helium cryogenic system, most half-open tubes or spaces will fall into the oscillations region, including the instrumentation line of the pressure transducer, cryogenic valve, closed bayonet connection, pressure relief line, and others. In a helium cryogenic system, instrumentation lines for pressure transmitters generally have an inner diameter of 4 mm, and pressure relief lines for safety valves range from 6 mm to 40 mm. The working conditions of these diameter tubes may fall into unstable regions.

3. EXPERIMENTAL SETUP

A test cryostat was designed and constructed to investigate the onset characteristics of half-open tubes inserted into the superfluid helium vessel. The cryostat was coupled to a superfluid cryogenic system in Institute of Modern Physics, China [11]. Five tubes with various diameters were used, commonly seen in helium cryogenic systems. The arrangement of tubes was similar to the practical design in the cryogenic system. All the tubes had a length of 1000 mm and different inner diameters (d = 4 mm,6 mm,10 mm,15 mm, and 25 mm).

The test cryostat and cryogenic system diagram are shown in Fig. 3. The test cryogenic system contained a helium refrigerator (Linde LR280), a 2000 L liquid helium dewar, a cryogenic valve box, a cryostat with a helium vessel, and a vacuum pump unit. The cryostat connected the valve box via a jumper connection. The cryostat had a diameter of 500 mm and a total height of 1000 mm, while the helium vessel had a maximum capacity of 30 L. The cold ends of the tubes were bent to U-shape to eliminate stress caused by thermal deformation. They were wrapped in 10 layers of high vacuum multilayer insulation (MLI). Liquid nitrogen was used for the thermal shield to reduce the heat load of the helium vessel. To make sure the cold end temperature was close as possible to 2 K, the liquid level was controlled near the cold open end.

Observed onset characteristics were based on the reliability of the measuring system. The liquid level sensor and monitor were supplied by Cryomagnetics, USA. Lakeshore Cernox-1030-AA and PT-100 were installed at the outer wall of the tubes, with a measurement accuracy



(a)

(b)

Fig. 3. Diagram of the test cryostat and cryogenic system.

of ±10 mK and ±(0.15 ~ 0.55)K, respectively. The pressure amplitude was measured by capacitance diaphragm gauge type pressure transmitters (Keller 41XE, Switzerland). The transmitters had a full-scale of 100 mbar and full-scale accuracy of ±0.1%. Each pressure transmitter was connected to the closed warm end via a ball valve. The sampling rates of pressure transmitters were up to 400 Hz, which were times bigger than possible frequencies as noted before. High-speed data acquisition could be achieved with a data acquisition board (National Instruments USB-6001, 14-bit, 20 kS/s/ch). Data storage and real-time display of the pressure were realized by the LabVIEW software package on a personal computer.

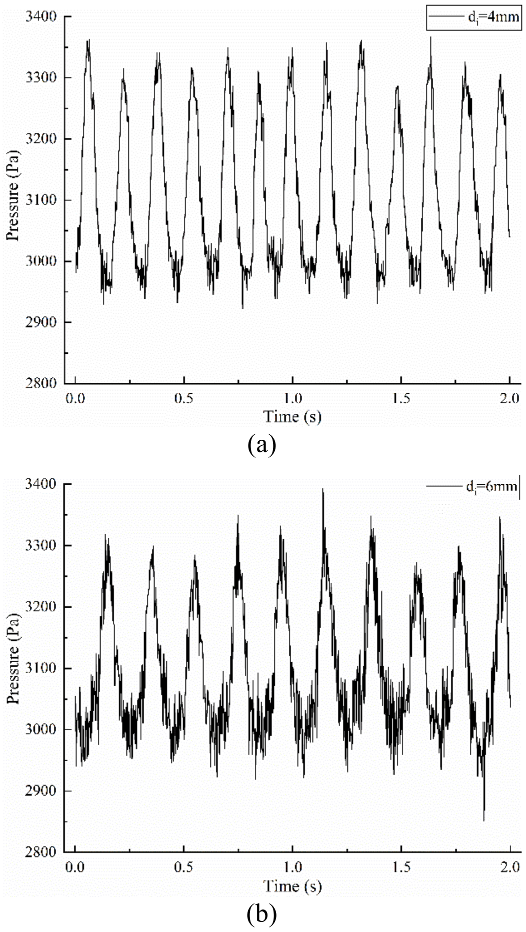
The acquisition of superfluid helium was based on the Joule-Thomson effect. With the help of a vacuum pump unit, liquid helium flowing through a J-T valve was transformed into superfluid helium. To improve throttling efficiency, a counter-flow heat exchanger was used to precool the liquid helium to 2.2 K. At first, the test cryostat was cooled down with liquid nitrogen. Then the cryostat was cooled down by liquid helium and filled with liquid helium. After cooling down, the liquid helium was transformed into saturated superfluid helium by regulating the J-T valve and pump unit. The suction of the pump unit could operate stably with pressure fluctuation of ±5.0 Pa around 3000 Pa, which was a little lower than the saturated pressure of 2.0 K because of the pressure drop of connecting pipe and heat exchangers.

3. RESULTS AND DISCUSSION

3.1. Onset characteristics of different tubes

After 2K superfluid helium was obtained in the vessel, pressure oscillations synchronously with time of some tubes were detected. At this time, the pressure amplitude in the tube with an inner diameter of 25 mm was not significant (±10 ~ 20 Pa). Pressure oscillations were observed in the other four tubes. As shown in Fig. 4, the pressure amplitude decreases with the increasing of tube diameter. The maximum amplitude ranged from 400 Pa to 250 Pa. In the 2 K operation mode of the cryogenic system, a PID control loop of pressure was often used to acquire a stable pressure (3100 Pa ± 30 Pa). Large pressure variations would lead to control failures and system instability.

The observed frequencies ranged from 3 Hz to 6 Hz, which are rather low compared to the theoretically predicted frequencies (around 30 Hz). The effect of liquid on oscillation frequency must be taken into consideration. On the one hand, as pointed out by Luck, when the open end of the tubes was not far away from the liquid level, waves may form on the liquid surface. Because of the additional mass, the frequency would be lower than pure gas oscillations [12]. On the other hand, when the gas with the mean pressure pm and a total mean volume V drives a liquid column of length s with liquid density ρ_{fl} in the tube of radius r, the frequency of gas-liquid oscillations ω_0 is calculated as follows[13]:



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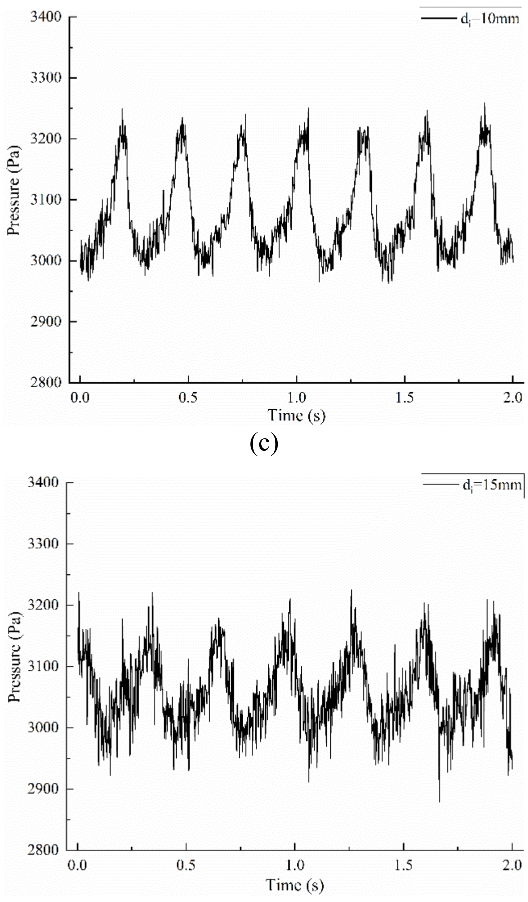

(c)

(d)

Fig. 4. Onset pressure characteristics of different tubes.

$$\omega_0 = \sqrt{\frac{\gamma p_m}{\rho_{fl}}\frac{\pi r^2}{sV}} \tag{3}$$

The frequencies ω_0 are remarkably lower compared to frequencies in tubes filled with gas alone. When the effect of gravity is taken into consideration, the frequency of oscillation is:

$$\omega_g = \sqrt{\omega_0^2 + 2g/s} \tag{4}$$

Where, s is the liquid column of length.

When the tube is inserted into the liquid, the calculated frequency is less than pure gas oscillation. The calculated frequency ω_g is 3.74 Hz for s = 10 cm. It can be qualitatively explained that gas-liquid oscillations are one of the main reason for lower frequency. The test heat load of 2K (≈3W) is almost the same as the oscillation-free cases at 4.2 K. It can be explained that the acoustic power and total power are low due to the low frequency and pressure amplitude.

3.2. Effect of temperature profile

Different temperature profiles could be realized by different cooldown rates. In the experiments, a fast cooldown was achieved in the first test within 2 hours. TAOs were not visible at d_i = 15 mm and d_i = 25 mm, as shown in Fig. 5. In Fig. 5, the symbol × indicated that TAOs did not occur, and the √ symbol indicated it occurred. In the second test, the vessel was cooled down within 8 hours. TAOs doesn't happen only in tubes of d_i=25 mm, as shown in Fig. 6. The difference in oscillation state for the 15 mm tube was quite different mainly because of the temperature profiles. It could be explained that when the tube profile was not as steep in a short section of the tube, there was an insufficient driving force to overcome the resistance. As explained by Swift [14], in a thermoacoustic engine or refrigerator, the temperature difference is the driving force of thermoacoustic oscillations and there must be a critical temperature gradient to stimulate TAOs. Similarly, in half-open tubes, a critical temperature gradient is also required.

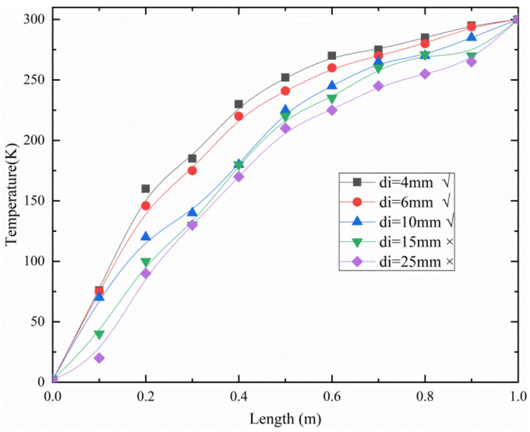

Fig. 5. Temperature profile of fast cooldown.

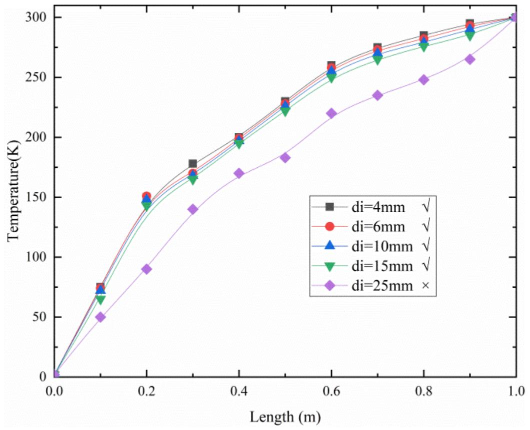

Fig. 6. Temperature profile of slow cooldown.

For oscillation-free cases, the recorded temperature profile approached linear distribution. Temperature profiles have a significant impact on TAOs. The tube with an inner diameter of 25 mm was smaller than the critical diameter according to the above analysis. TAOs might be prevented by circumfluence or natural convection caused by gravity and a large temperature gradient.

3.3. Damping strategy

To damp or eliminate TAOs in cryogenic systems, three main categories are usually adopted: (1) Proper tube design, such as enlarging the tube diameter or length. The system is generally considered stable when the tube diameter surpasses the critical diameter. As illustrated by the above experiments, a tube with large diameter is preferred for a half-open tube inserted into saturated superfluid helium. (2)

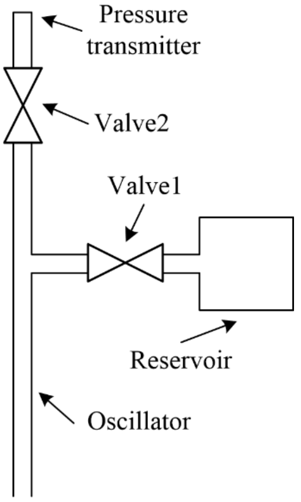

Fig. 7. Schematic drawing of an oscillator with dynamic damper.

Insertion of objects such as wire, wire mesh, or baffles into the oscillating column. These methods increase the turbulent losses of the tubes. TAOs may be damped by inserting a small rod into the oscillating tube, and the stability increased by a decrease in the annular gap [11]. (3) In many cases, geometry and temperature profiles cannot be freely chosen for limited installation space. With an adjustable Helmholtz resonator at the warm end of the half-open tube, oscillations may be eliminated. The most typical dynamic damper consists of a valve and a reservoir (as shown in Fig. 7 [12]). The valve1 can also be replaced by a capillary, an orifice, or other resistive devices. This approach is wildly used in liquid helium dewar.

The above method (2) could be used to eliminate TAOs by increasing the damping of given tubes. At the warm end, a control valve (Swagelok SS-4BK, valve2) with a maximum CV value of 0.36 was installed and linked to the pressure transmitter. The valve1 and reservoir were not installed. At first, the valve was fully opened, and the collected pressure amplitude was 300 Pa. By regulating the valve opening from full open to full closed, the pressure amplitude decreased to very low (±20 Pa), and the observed frequency shifted from regular to irregular. The transition opening was approximately 30 % full. In return, pressure oscillations would arise when the valve was turned on from completely closed to fully open. The pressure characteristics of turning on or turning off the valve are illustrated in Fig. 8.

For comparison, a needle valve replaced the control valve and served as the damper (valve 2). The maximum CV value of the valve is 0.004(Swagelok SS-SVR4). The collected pressure fluctuation always had a very low amplitude (±20 Pa) and no discernible frequency when adjusting the valve opening from fully open to completely closed or from completely closed to fully open. It could be explained that the control valve with a small opening and the needle valve with a small CV value could work as a damper. The frictional damping of the valves balanced the driving force generated by the temperature gradient.

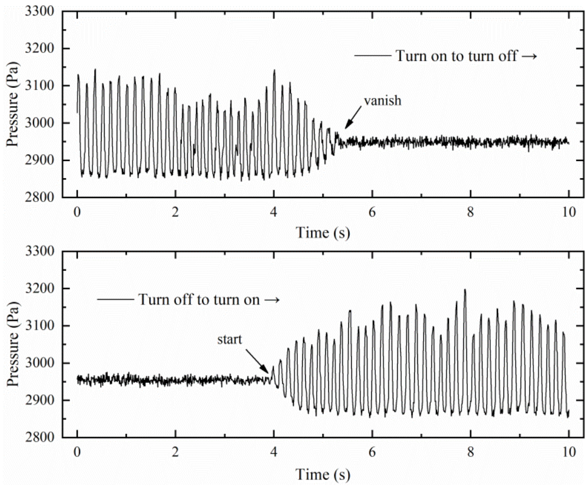

Fig. 8. Pressure characteristics of turning on or turning off the valve.

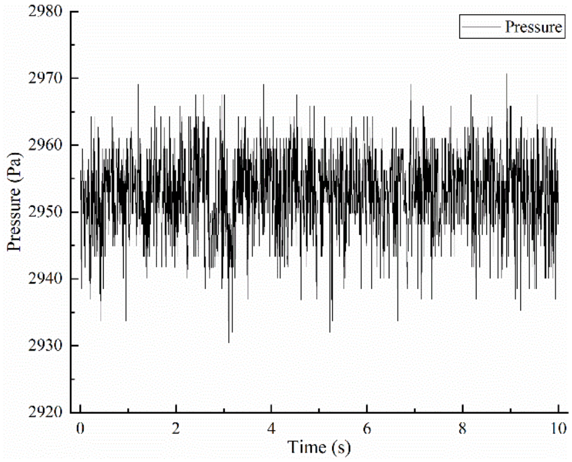

Fig. 9. Pressure characteristics of turning on or turning off the needle valve.

4. CONCLUSIONS

In this work, thermoacoustic stability analysis and experimental onset characteristics of half-open tubes inserted into saturated superfluid helium were investigated. The influences of tube geometry and temperature profile were discussed in detail. Gas-liquid oscillations and additional mass are the main causes of low frequency. The additional heat load due to low-frequency oscillation could be ignored. The temperature profile of a half-open tube has a considerable impact on TAOs. The damping supplied by a small mass flow valve at the hot end of the half-open tube inserted into saturated superfluid helium is sufficient to eliminate TAOs. This method may be employed in the instrumentation line of a pressure transmitter without any other design.

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