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# CFD Simulation of thermoacoustic oscillations in liquid helium cryogenic system

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## Abstract

Thermoacoustic oscillations (TAOs) could be often observed in liquid helium cryogenic system especially in half-open tubes. These tubes have closed warm end (300K) and open cold end (usually 4.4K). This phenomenon significantly induces additional heat load to cryogenic system and other undesirable effects. This work focuses on using computational fluid dynamics (CFD) method to study TAOs in liquid helium. The calculated physical model, numerical scheme and algorithm, and wall boundary conditions were introduced. The simulation results of onset process of thermoacoustic oscillations were presented and analyzed. In addition, other important characteristics including phase relation and frequency were studied. Moreover, comparisons between experiments and the CFD simulations were made, which demonstrated thevalidity of CFD simulation. CFD simulation can give us a better understanding of onset mechanism of TAOs and nonlinear characteristics in liquid helium cryogenic system.

*Keywords*: thermoacoustic oscillations, CFD simulation, onset characteristics

## 1. INTRODUCTION

Thermoacoustic oscillations (TAOs) are often observed in half-open tubes of hydrogen or helium cryogenic systems. In these tubes, cryogenic fluid moves to the warm end and evaporates. The vapor then pressurizes the hot end and drives the un-evaporated liquid back down to the cold end. If proper boundary conditions were met, such as sufficient warm to cold temperature ratio, particular geometry, and certain ambient pressure, self-sustained pressure oscillations could be triggered. This effect is often named as Taconis oscillations, first discovered by K.W. Taconis in 1949.

Taconis oscillations introduce extra cryogenic heat load by physically and efficiently moving cryogenic fluid between warm and cold ends, which could be much greater that from the intrinsic thermal conduction of the tube [1]. During LCLS-II prototype cryomodule test [2], TAOs were observed in both cryogenic distribution system and some cryomodule valves. The adverse effects brought by TAOs included not only four times of heat load comparing with the original design, but also pressure fluctuations in the cryogenic system, which eventually brought about ice formation on the oscillation sites. In addition, TAOs significantly contributed to microphonics of SRF cavities and degraded the performance of the entire accelerator.

Since Taconis oscillations is harmful to cryogenic system, after Taconis's discovery of this phenomenon, much theoretical and experimental research have been done to examine whether TAOs would exist under certain given conditions.

In 1969, Rott established the frequency-domain linear thermoacoustic theory [3-4]. He got a set of stability curves of three parameters including warm to cold temperature ratio, warm length to cold length ratio, and ratio of tube diameter to Stokes boundary layer thickness. These curves have two branches which are called lower branch and upper branch. Conditions under the lower branch and above the upper branch will be oscillation-free. After Rott's establishment of linear theory, a large amount of research was conducted to verify it. Experiments were done independently by Fuerst [1], Yazaki [5] and others [6-7]. They all concluded that TAOs could be predicted by liner theory with reasonable accuracy.

Nowadays, Rott's liner theory is the main method to predict TAOs in helium cryogenic system [8]. Step temperature profile along the half-open tube was adopted by Rott and most up-to-date researchers. For practical cryogenic system, temperature profiles along the tubes for different boundary conditions vary and are often continuous. Otherwise, gas helium with temperature down to 4.4K at saturated pressure could not be regard as ideal gas which means nonlinear effect should not be ignored. Recently, numerical simulation has been a useful method to study thermoacoustic phenomena [9-12], but little CFD simulation has been performed about TAOs in liquid helium cryogenic system. Thus, the main objectives of this work are: (1) use CFD simulation to characterize Taconis oscillations characteristics in liquid helium cryogenic system, which has not been studied by previous researchers yet. (2) Verify the reasonability of CFD simulation by comparing with experimental results of own and previous research. Through this study, a clearer understanding about the mechanism of Taconis oscillations in liquid helium cryogenic system would be obtained.

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## 2. CFD MODELING FEATURES

All numerical calculations presented were performed by using the Ansys-FLUENT software package, which is one of the most widely used CFD codes for its convenience and credibility. The nonlinear Navier-Stokes equation, mass and energy equations are solved by FLUENT 18.2 based on finite volume method.

### 2.1. Numerical model details

Typical Taconis oscillation tube model for simulation is showed in Fig.1. The tube has an open cold end and a closed warm end. The length direction is set as $x$ direction where the radial direction is set as $r$ direction. The tube diameter is 4 mm which is commonly used in practical cryogenic system. Compared with one-dimensional models, a two-dimensional axisymmetric model is adopted for the domain, which is acceptable and time-saving in contrast to three-dimensional models.

The working gas is helium. The operating pressure is 120000Pa (saturated vapor pressure of liquid helium at 4.4K). For gas helium with temperature down to 4.4K at this pressure, helium could not be regard as ideal gas. All the gas helium properties, including density, viscosity, thermal conductivity and sound velocity are temperature (T) dependent, isolated data points can be obtained from Hepak software package. The above properties were then fitted to exponential type functions and imported into Ansys software. The important calculation parameters and functions are given in Table 1.

For the closed warm end, the temperature is set as 300K. The open cold end is set as pressure outlet boundary. The gauge pressure is 0Pa. The temperature of open cold end is 4.4K. The main numerical schemes used in this work are listed in Table1. Owing to get onset characteristics, transient calculations for unsteady flow need to be performed. Transient calculation is conducted with an initial pressure distribution along the $x$ direction after steady solve. The initial pressure distribution along the tube is set as sinusoidal function. Different fixed time steps were used for different cases which range from $1.0\times10^{-5}$s to $2.0\times10^{-5}$s. Each time step needed no more than 100 iterations to reach convergence with reasonable precision. Grid independence was achieved by comparing among different sized structural grids, and a mesh with 16,016 nodes was finally chosen for the balance between calculation accuracy and period. The initial conditions, properties, numerical schemes and the main applied boundary conditions except tube wall boundary are summarized in Table 1.

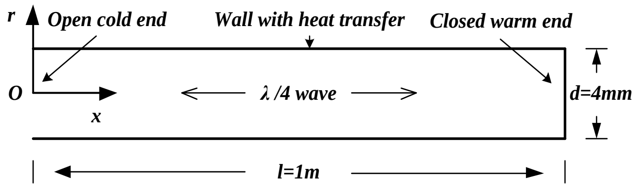

Fig. 1. Typical Taconis oscillations tube model.

TABLE I

NUMERICAL CALCULATION CONDITIONS OF CFD SIMULATION.

| | |
|---|---|
| Working gas | Helium |
| Operating pressure | 120000Pa |
| Cold/warm end temperature | 4.4K/300K |
| Density | $\rho=125.14\times T^{-1.31952}$ kg/m$^3$ |
| Viscosity | $\mu=5.123e^{-7}\times T^{0.64023}$ Pa-s |
| Thermal conductivity | $\lambda=0.00345\times T^{0.66751}$ W/m-K |
| Sound velocity | $c=57.1313\times T^{0.50568}$ m/s |
| Initial pressure distribution | $p_{initial}=100\times\sin(\pi x/2)$ Pa |
| Solver | Segregate |
| Viscous model | Laminar |
| Pressure–velocity coupling | Coupled |
| Spatial discretization of pressure | PRESTO! |
| Spatial discretization of density, momentum, and energy equations | Second-Order Upwind |

### 2.2. Tube wall boundary condition analysis

In practical cryogenic system, wall boundary conditions of half-open tubes are quite different. In reality, high vacuum multilayer insulation tubes (MLI) are often used to minimize heat load. Typical half-open tubes of this kind are instrumentation lines of pressure transmitters and pressure relief lines. In these cases, heat transfer from convection and conduction of residual gas could be ignored. Only radiation heat transfer is taken into consideration. To simplify the calculations, the angle factor and surface area ratio of warm to cold are both assumed as 1. The heat flux density $q_1$ for thermal insulation tubes could be calculated as a function of the number of intermediate surfaces for MLI:

$$q_1=\frac{1}{n+1}\frac{\sigma\varepsilon}{2-\varepsilon}\left(T_{warm}^4-T_{cold}^4\right) \tag{1}$$

Where $\sigma$ is Boltzmann constant, $\varepsilon$ is emissivity of aluminum, $n$ is the layer number of MLI, $T_{\text{warm}}$ is the temperature of the ambient environment, $T_{\text{cold}}$ is the temperature of the cryogenic end.

For some cases in helium cryogenic system, high vacuum multilayer insulation tubes could not be employed, such as tubes inserted into Dewar and though bayonet connection. All the heat transfer could be transferred to convection type. The heat flux density $q_2$ of non-thermal insulation tubes could be calculated as a function of the number of intermediate surfaces for MLI:

$$q_2=h\left(T_{warm}-T_{cold}\right) \tag{2}$$

Where $h$ is the heat transfer coefficient, including convection and radiation heat transfer. $T_{\text{warm}}$ and $T_{\text{cold}}$ have the same definition as Eq.1.

As Rott's [3] and Gupta's [8] calculations, practical oscillations tube in liquid helium with the length of 1m, whose diameter is smaller than 30mm has risk of pressure oscillations (just the lower stability curve of Rott's analysis is taken into consideration.). In order to compare with their analysis, the length ratio of warm end to cold end ($\xi$) is assumed to 1.

## 3. CFD RESULTS AND DISCUSSION

### 3.1. Self-excited thermoacoustic oscillation

In the process of simulation, the point of $x$ = 0.10m on the axis is set as monitor point of pressure. For different wall boundary conditions of tubes, temperature profile will be quite different (as shown in Fig.2). We name the temperature profile from profile 1 to profile 5. For perfect thermal insulation tube (only radiation is considered), the temperature distribution is named as profile 1. For partially thermal insulated tubes, the temperature distribution vary with heat transfer coefficient between cold parts and warm parts. The heat transfer coefficient ranging from 0.01 $W \cdot m^{-2} \cdot K^{-1}$ (profile 2) to 10 $W \cdot m^{-2} \cdot K^{-1}$ (profile 5) is studied in this work. The results plotted in Fig.2 agree with the intuitive idea, that as the heat transfer coefficient becomes bigger, the slope of the profile will also be larger.

Fig.3 shows a typical pressure fluctuation in the tubes without self-sustained oscillations through CFD simulation. For profile 1, 2, and 3 showed in Fig.2, the temperature gradient in the middle of the tube is not large enough, therefore any initial pressure perturbation will diminish by itself. In a word, TAOs will not occur in tubes with such profiles.

When the temperature gradient along the tube exceeds a critical value, thermoacoustic oscillations will occur spontaneously. For profile 4 and 5 showed in Fig.2, self-growing pressure fluctuations could be observed on the CFD simulation results. The pressure amplitude is related to the temperature gradient in the middle of the tube. It takes less time to achieve stable state for larger gradient.

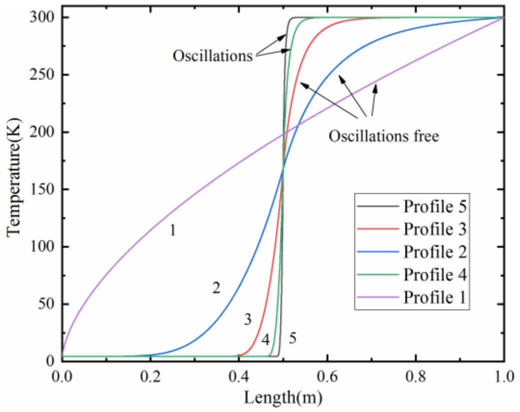

Fig. 2. Temperature profiles along the tube under different wall boundary conditions.

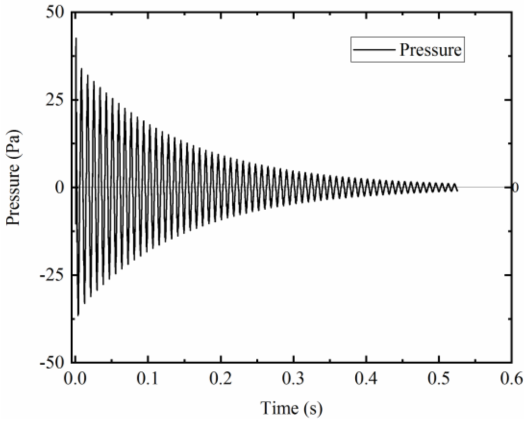

Fig. 3. Typical pressure oscillations in tubes with oscillation-free profiles though CFD simulation.

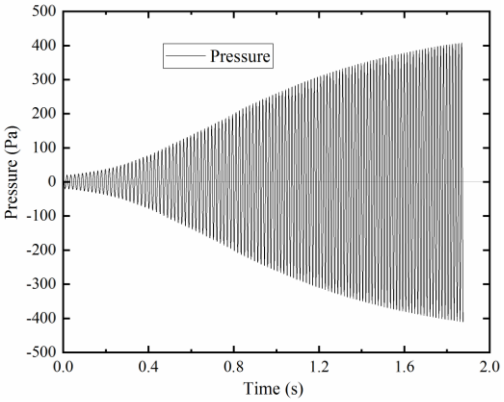

Fig. 4. Process of self-excited pressure oscillations of profile 4 in Fig. 2.

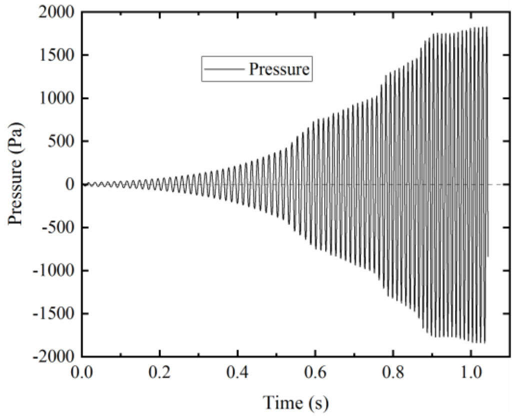

Fig. 5. Process of self-excited pressure oscillations of profile 5 in Fig. 2.

For profile 4, the pressure amplitude ascends to 0.41 kPa (gauge pressure) within 1.9 s (as shown in Fig.4). For profile 5, the pressure amplitude ascends to 1.83 kPa (gauge pressure) within 1.05 s (as shown in Fig.5). In these two cases, the sharp changes of environment can generate enough driving force which succeeds the damping force, and TAOs can be stimulated. As the ascending of the mean pressure, the damping force becomes larger and will balance with the driving force. Finally, maximum amplitude will be reached and sustained oscillations will be set up.

### 3.2. Phase and frequency analysis

Fig.6 and Fig.7 present the phase relation between pressure and $x$-component velocity of stable oscillations. In stable oscillation cycle, the time that the x-component velocity reaching the peak point is earlier than the pressure. For profile 4 (as shown in Fig.6), the velocity is 0.0026s ahead of pressure, and the phase difference is 91.72° (about 1/4 cycle). For profile 5 (as shown in Fig.7), similar results can be obtained. According to Rayleigh's criterion [13], to stimulate and maintain sustained TAOs, there must be phase difference between the process of heat transfer and flow. CFD results are in accordance with Rayleigh's hypothesis.

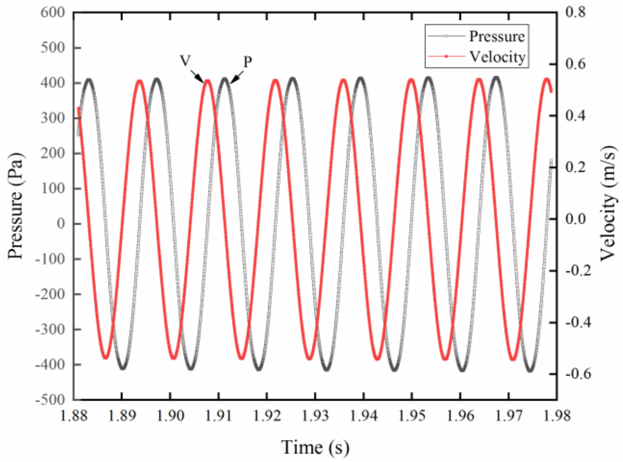

Fig.6. The phase relation between pressure and *x*-component velocity for profile 4 in Fig. 2.

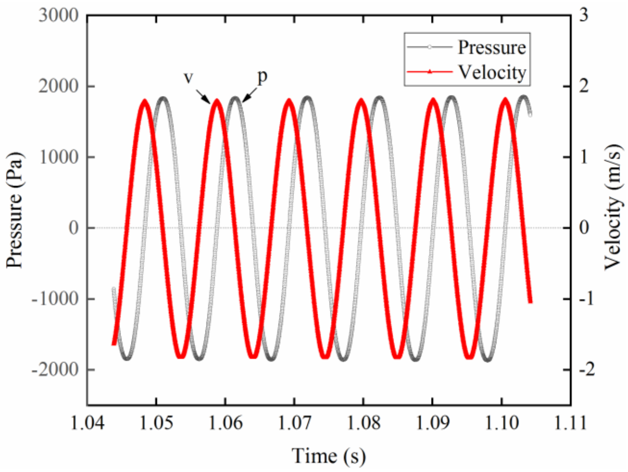

Fig.7. The phase relation between pressure and *x*-component velocity for profile 5 in Fig. 2.

The main damping force is friction, and will be balanced with driving force when the equilibrium is reached. On the basis of Darcy's formula, the frictional pressure drop is in proportion to velocity amplitude for laminar flow. Compared between Fig.6 and Fig.7, the driving force of profile 5 is 3.2 times larger than profile 4. When the temperature gradient is large enough or close to step function, the flow in cold region of the tube may have the opportunity to generate flow transition from laminar flow to turbulent flow.

After stable oscillation of CFD simulation, fast Fourier transform (FFT) analysis was conducted to aquire the frequency. According to Rott's theory, for given condtions, the frequency could be caculated by equation (53) and (69) in his paper[3]. For our simulation case, the frequency value according to linear theory is about 30 Hz. By CFD simulation, the caculated frequency is 95.79 Hz, which is much higher than the value caculated by linear theory. It means that the higher order terms of pressure and velocity could not be neglected for TAOs in liquid helium. The large discrepancy between the laminarly flowing ideal gas and the CFD suggests that TAOs in liquid helium cryogenic system should be treated as a kind of nonlinear phenomenon.

## 4. COMPARISON WITH EXPERIMENTAL RESULTS

In order to evaluate the rationality of CFD simulation, experimental validations were conducted. In real cryogenic system, a half-open tube with thermal insulation or non-thermal insulation does not coexist. To verify CFD simulation results for thermal insulation tubes, a newly designed device is used to observe TAOs in liquid helium. For non-thermal insulation tubes, we make comparisons with previous research.

### 4.1. Experimental setup for thermal insulation tube

The schematic diagram of test cryostat is showed in Fig.8. The experimental cryostat is with diameter of 500 mm and total height of 1000 mm, having a maximum capacity of 30L. Liquid helium comes from a 2000L helium Dewar of the helium refrigerator (Linde LR280) via valve boxes. A tube with total length of 1000 mm and diameter of 4 mm was installed. To eliminate the stress from thermal deformation, cold end of the tube is bent to U-shape. To make the cold end temperature as close as possible to 4.4 K, the liquid level must be controlled near the cold open end. After cooling down of the cryostat, by regulating pressure with the help of valve and helium compressor, the small variation of pressure signal could be acquired.

The tube was equipped with twelve resistance temperature sensors (Lakeshore Cernox-1030-AA and PT-100) and 20 layers of MLI at most. In order to better reflection of time-correlated pressure oscillations, high-frequency dynamic pressure transmitters with sampling rate up to 5 kHz were used. In actual measurement, sampling rate was set as 1 kHz in the light of Nyquist sampling theorem. The piezoelectric type pressure transmitter (Keller) with pressure range from 0 Bara to 2 Bara and accuracy of ±0.2% full scale were used to measure the peak to peak pressure amplitude at the closed warm end. A data acquisition board (Advantech PCI-1716 250KS/s) could realize high speed data acquisition. LabVIEW software package installed on a host computer was in charge of the data storage, measurement control, and real-time display of the results.

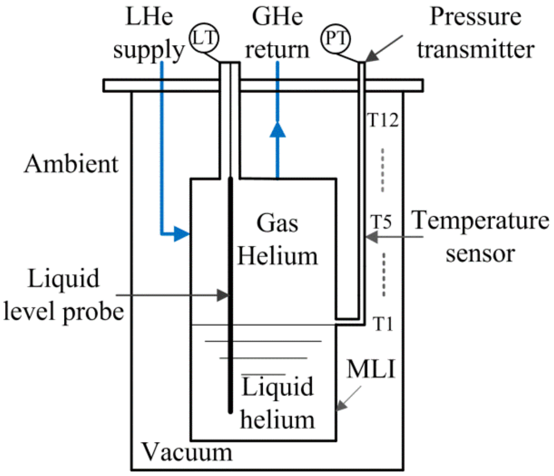

Fig. 8. Schematic diagram of the test cryostat.

### 4.2. Comparison with thermal insulation tubes

Fig.9 gives the comparison of tube temperature between the simulated and the experimental results for a tube with good thermal insulation. It can be seen that the calculated result (profile in Fig.2) agree well with the experimental values. Fig.10 shows the experimental results of pressure amplitude under the operating pressure around 1.2 bara. The typical pressure fluctuation in this tube is ±2mbar（the max range is ±3mbar). Moreover, spectrum analysis of the pressure could not get valid frequency value which means it is not periodic signal. Take the measurement accuracy of pressure transmitters and regulating ability of helium cryogenic system into consideration, we can conclude that TAOs has not occurred in the test system.

The length ratio of warm end to cold end (ξ) is around 2. According to Rott's model, the tube with the length ratio has risk of oscillations with discontinuous temperature profile. CFD simulation results have good agreement with experiment results. It can be concluded that half-open tube with good thermal insulation has lower probability of TAOs in liquid helium cryogenic system. The linear theory did not consider the effects of other temperature profiles, thus may reduce wrong prediction the TAOs and lead to over conservative engineering design [8]. For example, to avoid TAOs in instrument line of pressure transmitter in liquid helium, the diameter of tube would be too large according to reference 8.

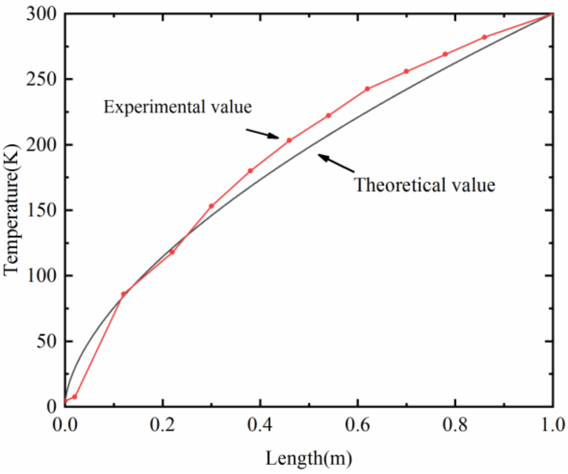

Fig. 9. Comparison of tube temperature profiles between simulation and experiment under good thermal insulation.

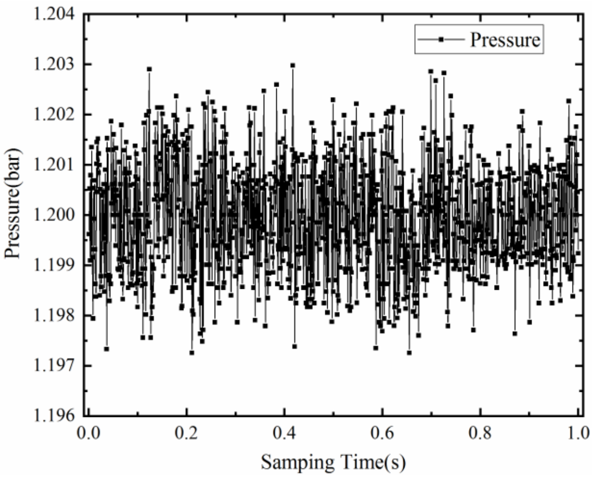

Fig. 10. Pressure variation of experimental results for good thermal insulation tube.

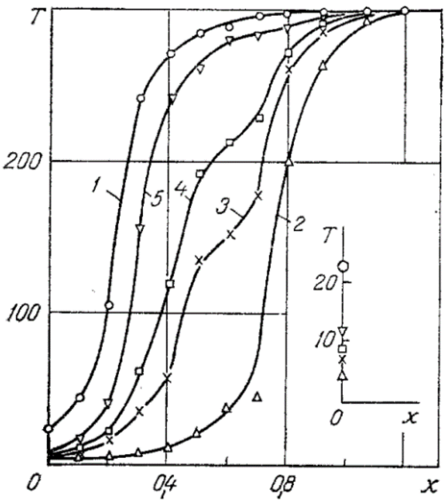

Fig. 11. Temperature profile dynamics in tube of Gorbachev's experiment.

### 4.3. Comparison with non-thermal insulation tube

Fig.11 presents Gorbachev's [6] experimental results of temperature profile along a Φ-4 mm tube. The feeding cold gas flowed along the outer surface of the tube. The heat transfer coefficient increases as the flow became larger and the temperature profile changes from curve 1 to curve 2(1→5→4→3→2). The TAOs was only stimulated in the tube at the curve 2 state. When the temperature gradient in the middle of the tube became large enough (the length ratio ξ was around 1 for curve 2). When the feeding gas was turned off gradually, the temperature profile changes from curve 2 to curve 1(2→3→4→5→1). The maximum temperature gradient became lower and the amplitude of pressure appeared to be lower until it disappeared. This phenomenon indicated that hysteresis phenomenon also exists in the process of Taconis oscillations. Gorbachev's results could be a good reference to our results in the sense that the length ratio in his work is nearly as same as ours. From the above comparison, we can conclude that not only a steep temperature gradient, but also the temperature transition location is critical to the occurrence of TAOs.

## 5. CONCLUSIONS

In this work, a commercial CFD code was applied to simulate TAOs of half-open tube in liquid helium cryogenic system for the first time. Modeling and simulating of the tube under different wall boundary conditions have been accomplished. Moreover, comparisons with actual experiments have been done to verify the validity of the CFD simulation. The main results of this study are summarized as follows:

(1) The entire self-excited process of dynamic pressure of TAOs in liquid helium has been successfully studied with simulation. Various temperature profiles caused by wall boundary conditions have different oscillation

characteristics. To stimulate TAOs, large temperature gradient along the tube length direction is needed to generate enough driving force.

(2) Through phase analysis of pressure and velocity, the pressure is ahead of the velocity with 1/4 cycle. The Rayleigh's criterion is verified as the key factor to stimulate and maintain the sustained TAOs. Nonlinear frequency characteristic is obtained by CFD simulations.

(3) Comparisons between CFD simulations and experimental results for different conditions show good agreement with each other. It demonstrates that the CFD simulation is a useful method to study complicated, nonlinear effects of TAOs in liquid helium cryogenic system. It is a useful way to predict TAOs.

(4) However, because of difficulties in measuring accurate boundary conditions under practical circumstances, precise prediction of TAOs in real cryogenic systems is still difficult. For better understanding of thermoacoustic performance in liquid helium cryogenic system, more effects are still needed to be considered, such as 3D physical model influence, gas-liquid oscillations and other nonlinear phenomena.

## ACKNOWLEDGMENTS

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