

A STANDING-WAVE THERMOACOUSTIC ENGINE DRIVEN BY LIQUID NITROGEN

K. Wang, L.M. Qiu^{*}, B. Wang, D.M. Sun, P. Lou, J.F. Rao, and X.J. Zhang

Institute of Refrigeration and Cryogenics, Zhejiang University
Hangzhou 310027, P.R. China

ABSTRACT

Thermoacoustic oscillation at cryogenic temperatures, such as Taconis oscillation, has been typically suppressed in the former studies, and few efforts have been made to enhance it. We proposed a standing-wave thermoacoustic engine (TE) driven by liquid cryogenics instead of the conventional heat to enhance the thermoacoustic effects and utilize the cold energy. Experimental and theoretical work has been performed on a self-made standing-wave TE to demonstrate the feasibility and the operating characteristics of the engine driven by the liquid nitrogen. Experiments show that with nitrogen at 0.5 MPa as a working gas, a pressure ratio of 1.21 is obtained on the TE driven by liquid nitrogen with a much lower temperature difference along the stack compared to that of the conventional TE. The onset temperature difference decreases by 28.9% with helium at 0.63 MPa as a working gas, compared to that of the conventional TE. This study verifies the feasibility of enhancing the thermoacoustic oscillation at cryogenic temperatures. The TEs driven by liquid cryogenics such as liquid nitrogen and liquefied nature gas (LNG), may be an alternative for recovering the cold energy.

KEYWORDS: Thermoacoustic engine, liquid nitrogen, LNG, cold exergy

INTRODUCTION

A TE converts thermal energy into acoustic power via thermoacoustic effects with no mechanical moving parts. It is reliable and potentially highly efficient; comparable to an internal combustion engine [1]. What is more attractive is that TEs may utilize low-grade thermal energy directly, which is promising for energy-saving.

Until recently, nearly all TEs have been driven by heat sources above the ambient temperature, normally as high as 870 K [1-5]. We name the heat driven thermoacoustic

^{*} Author to whom correspondence should be addressed. Electronic mail: Limin.Qiu@zju.edu.cn

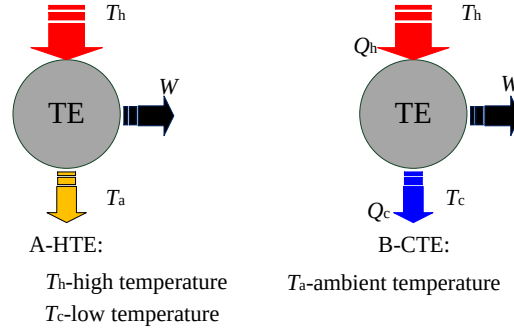


FIGURE 1. Thermoacoustic engines with different driving methods: (A) The heat driven Thermoacoustic Engine (HTE). The TE is driven by heat energy and the cold end of the stack is kept at room temperature; (B) The cold energy driven Thermoacoustic Engine (CTE). The cold end of the stack is cooled by liquid nitrogen and the hot end of the stack is driven by heat energy. $T_c < T_a < T_h$, and W is the work.

engine as HTE (FIGURE 1A). Thermoacoustic oscillation at cryogenic temperatures was studied by Keesom in 1942 [6] and qualitatively explained by Taconis in 1949 [7], after which “Taconis oscillation” was named. The first experimental measurement of the oscillation at cryogenic temperatures was made by Clement et al. in 1954 [8]. The linear thermoacoustic theory on the Taconis oscillations was developed by Rott [9-11] and further nonlinear analysis was made by Yazaki et al. [12,13] and Shimizu et al. [14-16]. Yazaki et al. conducted experimental research on the stability curves and the frequency diagram of the oscillation in 1979 [13,17]. A thermoacoustic oscillator cooled by liquid nitrogen at the cold end was designed by Wheatley et al.. The time development of the oscillations was tested and the peak-to-peak maximum oscillation reached 11% of the ambient pressure in a steady state (i.e., pressure amplitude is 5.57 kPa) [18]. In 1993, Luck et al. built a TE cooled by liquid nitrogen obtained a maximum pressure amplitude of 3 kPa. Unfortunately, no net power was withdrawn [19].

The former studies about the thermoacoustic oscillation at cryogenic temperatures are mainly focused on the mechanism of the thermoacoustic oscillation and then suppressing it. In fact, it is possible to drive a TE by liquid cryogenics, such as LNG and liquid nitrogen. Although Luck showed a good prospect (e.g., cold compressor) of the TE driven by liquid cryogenics [20], no further efforts have been made to enhance and utilize thermoacoustic oscillations at the cryogenic temperatures and explore the operating characteristics of the TE with cold energy since then. This study proposed a self-made standing-wave TE driven by liquid nitrogen. We name the thermoacoustic engine driven by cryogenics as CTE (FIGURE 1B). Theoretical and experimental work has been performed to demonstrate the feasibility of it and explore the differences of the operating characteristics between CTE and HTE.

THEORETICAL PREDICTION

FIGURE 2 shows the schematic of the self-made standing-wave TE. Dimensions of the TE are listed in TABLE 1.

The critical temperature gradient along the stack of the TE is derived on the basis of linear thermoacoustic theory. The working gas is assumed to be inviscid. The temperature gradient at any position of the stack is given by [21]

$$\nabla T_{\text{crit}} = \frac{\omega A |p_1|}{\rho_m C_p |U_1|} \quad (1)$$

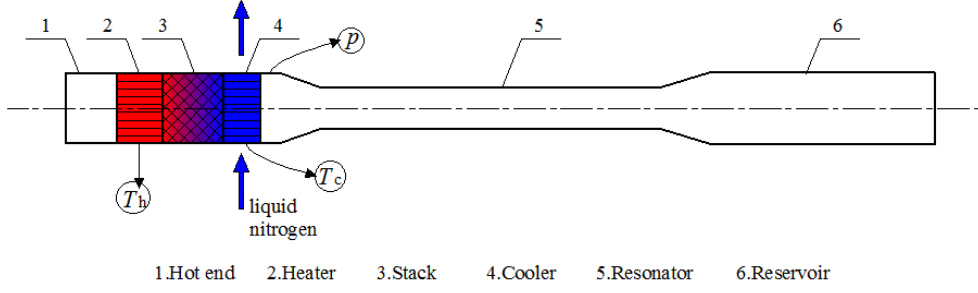


FIGURE 2. Schematic of the standing-wave TE. Symbol p shows the location of pressure sensor. Symbols T_h and T_c show the locations of the temperature sensors.

TABLE 1. Dimensions of the standing-wave TE

	Hot end	Heater	Stack	Cooler	Resonator	Reservoir
Diameter (mm)	50	50	50	50	32	81
Length (mm)	60	77	60	50	860	850
Stack material	18# stainless screen					

where

- ω is the angular frequency,
- A is the cross-sectional area of the stack,
- ρ_m is the mean gas density,
- C_p is isobaric heat capacity per unit mass of gas,
- p_1 is the pressure amplitude,
- U_1 is the volume flow rate.

Onset indicates the transition of a TE from the stationary to periodic oscillating state. When the temperature gradient of the stack $|dT_m/dx|$ is larger than ∇T_{crit} , the working gas in the TEs starts oscillating. The angular frequency can be given by

$$\omega = 2\pi f = 2\pi a / \lambda = 2\pi \sqrt{\gamma R_g T_m} / \lambda \quad (2)$$

where

- f is frequency,
- a is the sound speed,
- λ is the wavelength,
- γ is the ratio of isobaric to isochoric specific heats,
- R_g is the gas constant,
- T_m is the mean temperature of the working gas.

Equation (1) and (2) produce,

$$\nabla T_{\text{crit}} = \frac{2\pi \sqrt{\gamma R_g T_m} A |p_1|}{\lambda \rho_m C_p |U_1|} = \frac{2\pi \sqrt{\gamma R_g} A |p_1| \sqrt{T_m}}{\lambda C_p |U_1| \rho_m} \quad (3)$$

Where γ , R_g and C_p are dependant on the properties of the working gas, and λ is only dependant on the dimension of the TE. They are constants for a specific working condition of a specific TE. We define a constant C under the assumption that $|p_1|/|U_1|$ is a constant,

$$C = \frac{2\pi\sqrt{\gamma R_g} A |p_1|}{\lambda C_p |U_1|} \quad (4)$$

Thus,

$$\nabla T_{\text{crit}} = C \frac{\sqrt{T_m}}{\rho_m} \quad (5)$$

∇T_{crit} multiplied by the stack length can be used to estimate the critical temperature difference of the stack $(T_h - T_c)_{\text{crit}}$ at the onset moment, which is called onset temperature difference. As shown in equation (5), the onset temperature difference decreases significantly when the temperature of the working gas decreases and the mean gas density increases due to the temperature decrease of the gas. FIGURE 3 shows dependence of the critical temperature difference on cooler temperature. With helium as a working gas, taking the working pressure of 0.63 MPa as example, the onset temperature difference ($T_c = 90$ K) is only 16.4 % of that when T_c is 300 K. It shows the tendency that the onset temperature difference can be significantly decreased when the cold end of the stack cooled by the liquid nitrogen.

DeltaEC (Design Environment for Low-amplitude ThermoAcoustic Energy Conversion) [22] was used to predict the performance of CTE with helium as working gas. The heating power was maintained at 100 W and the cooler temperature T_c changed from 300 K to 40 K. The working pressures of 0.63 MPa, 0.9 MPa, 1.2 MPa, 1.5 MPa, and 2.2 MPa were chosen in calculations. The ambient temperature T_a was 300 K. The heat exchanged in the cooler was obtained by calculation.

Under all the working pressures, decreasing T_c (i.e., lowering the temperature of the working gas) in a TE leads to the increase of the pressure amplitude, as shown in FIGURE 4(A). For example, at a working pressure of 0.63 MPa, the pressure amplitude increases by 81.5% from 0.027 MPa to 0.049 MPa when T_c decreases from 300 K to 40 K. Such an increase in the pressure amplitude is obtained with a smaller $T_h - T_c$, see FIGURE 4(B). $T_h - T_c$ decreases from 559.2 K to 76.2 K when T_c changes from 300 K to 40 K when the working pressure is 0.63 MPa. Obviously, cooling the cold end of the stack leads to the temperature decrease of the working gas, which reduces $T_h - T_c$ and increases the pressure amplitude.

It should be noted that the above improvement is obtained with a heating power of 100 W at the hot end of the stack besides of the use of cryogen. Therefore, the exergy efficiency should be taken into consideration to evaluate the performance of the CTE. FIGURE 5 shows the exergy efficiency curve of CTE, the definition is

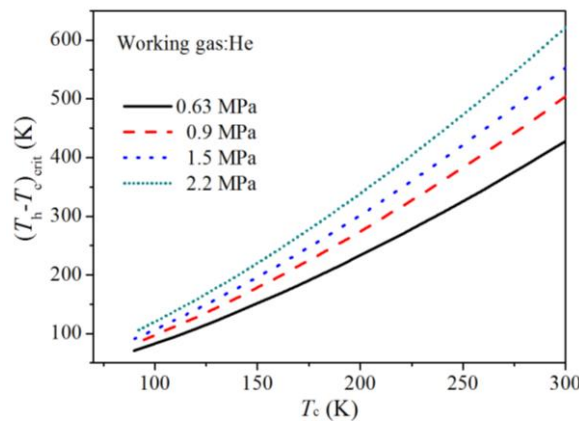


FIGURE 3. Dependence of the critical temperature difference on cooler temperature

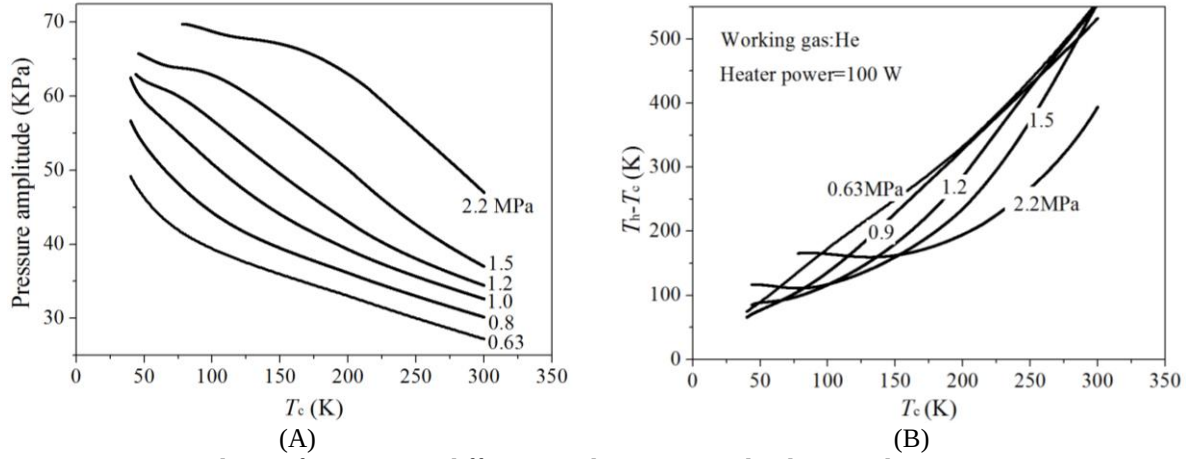


FIGURE 4. Dependence of temperature difference and pressure amplitude on cooler temperature

$\eta_e = W / [Q_h(1 - T_a / T_h) - Q_c(1 - T_a / T_c)]$, where W is the acoustic power in location p (see FIGURE 2). Under lower working pressures (e.g., 0.63 MPa, 0.9 MPa), the exergy efficiency η_e decreases with T_c . While under higher working pressures (e.g., 1.5 MPa, 2.2 MPa), lowering the temperature of the cold end is beneficial for increasing η_e , as the peak value appears when T_c is at cryogenic temperatures. It is possible in CTE to obtain higher exergy efficiency by using liquid nitrogen to cool the cold end of the stack. The calculation with nitrogen as working gas shows the similar tendency with helium.

EXPERIMENTAL PERFORMANCE OF CTE

Helium as working gas

Experiments have been conducted to test the standing-wave TE to verify the theoretical prediction. A calibrated platinum resistance thermometer Pt-100 and a calibrated NiCr-NiSi thermocouple were installed to measure T_c and T_h as shown in FIGURE 2. All measured temperatures are the wall temperatures due to the difficulty of the measurement of gas temperatures. The pressure p shown in FIGURE 2 was measured by a calibrated piezoelectric ceramic pressure sensor with an accuracy of $\pm 0.3\%$ and temperature influence on the accuracy is negligible ($\pm 0.015\%$ fs/K).

Three cooling and heating ways are compared in the TE with helium at 0.63 MPa. The

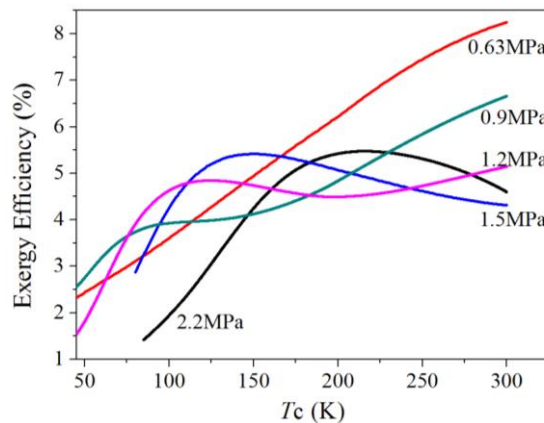


FIGURE 5. Dependence of Exergy efficiency on the cooler temperature

first way is to lower the cooler temperature by using only liquid nitrogen. Unfortunately, the TE cannot reach the onset state because of the insufficient temperature difference between the both ends of the stack. Then the additional heat is added into the heater after T_c reaches the liquid nitrogen temperature range, the TE reaches the onset state when T_c is 119.0 K and T_h is 283.6 K. T_c ranges from 119.0 K to 132.3 K after onset. We call this temperature range as low temperature range. The second way is to lower T_c by liquid nitrogen and simultaneously increase T_h at the beginning of the experiment. The TE reaches the onset state when T_c is 265.6 K, after onset T_c changes within the range of 265.6-187.4 K. We call this temperature range as middle temperature range. The third way is the traditional way as HTE, of which ambient-temperature water is used to maintain T_c at a constant temperature, and the heater is added heat into the TE. The TE onsets and T_c is kept at 285.0 K. This temperature range is called ambient temperature range. From the viewpoint of energy conversion, the TE driven by the first and second ways is CTE.

FIGURE 6 compares the pressure amplitude at these three temperature ranges. The temperature difference $T_h - T_c$ is the smallest at the low temperature range while it is the largest at the ambient temperature range. Compared with the temperature difference $T_h - T_c$ at ambient temperature ranges, the value of $T_h - T_c$ decreases by 28.9% and 13.1% at the low and middle temperature ranges (see TABLE 2), which proves that lowering the gas temperature is beneficial for decreasing the onset temperature difference. After onset, for the same $T_h - T_c$, the highest pressure amplitude is obtained with the working gas at the low temperature range and the lowest is obtained at the ambient temperature range. The experiments verify the benefits of lowering the gas temperature by liquid nitrogen obtained from calculation. When CTE works between 300.1 K at the hot end and 124.8 K at the cold end of the stack, a pressure amplitude of 6.64 kPa is obtained.

FIGURE 7 is the comparison of the frequency between the calculations and the experiments. The frequency changes with the mean temperature T_m ($T_m = (T_h + T_c) / 2$, which reflects the mean temperature of the stack). It decreases with the working gas temperature, because the sound speed a ($a = \sqrt{\gamma R_g T_m}$) decreases with the mean temperature T_m and the

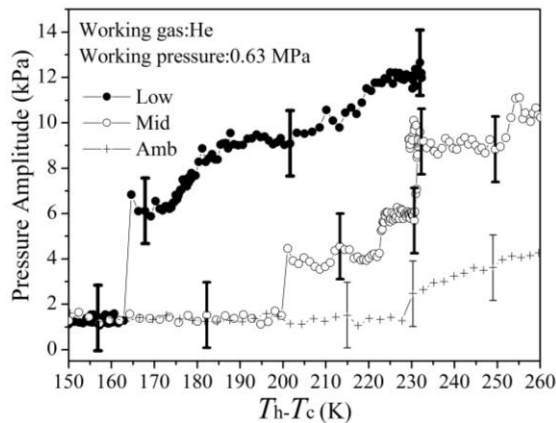


FIGURE 6. Comparison of the pressure amplitude curve at low, middle and ambient temperature range.

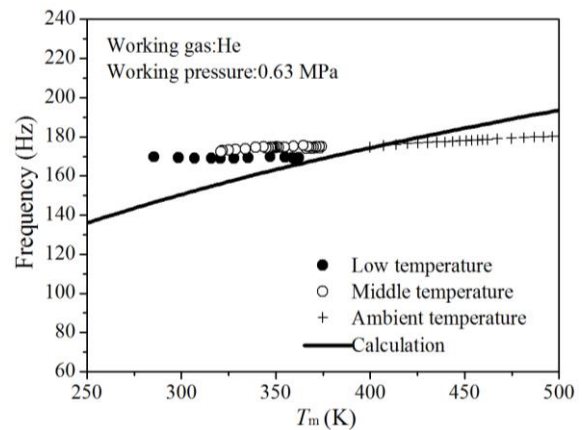


FIGURE 7. Experimental and calculation comparison of frequency changing with temperature

TABLE 2. The cooler temperature and temperature difference at the onset moment at the three temperature ranges

	T_c (K)	$\Delta T = T_h - T_c$ (K)	Decrease of ΔT (K)	Decrease of ΔT (%)
Amb	283.6	231.4		
Mid	265.6	201.1	30.3	13.1
Low	119.0	164.6	66.8	28.9

wavelength λ is a constant (the frequency $f = a/\lambda$, λ does not change as the dimension of the TE is fixed).

Nitrogen as working gas

In experiments, CTE obtains the highest pressure amplitude with nitrogen as a working gas. FIGURE 8 shows the performance of the CTE with nitrogen as a working gas.

The performance of CTE and HTE with nitrogen at 0.5 MPa is compared in FIGURE 8. At the beginning of the experiment, the CTE is only cooled at the cold end of the stack by liquid nitrogen (without adding additional heat at the hot end), which can make the TE onset. After onset, additional heat is added to the TE. Pressure ratio of 1.21 is obtained in the CTE when $T_h - T_c = 377.9$ K, while in the HTE (the cold end of the stack is maintained at room temperature and hot end is at higher temperature) a much larger temperature difference is needed (as large as 634.0 K). For the same pressure amplitude of 45.02 kPa (i.e., pressure ratio of 1.21), the requirement of $T_h - T_c$ for the CTE decreases by 40.4% compared to that for the HTE. When $T_h - T_c = 422.0$ K ($T_h = 574.0$ K and $T_c = 152.0$ K), highest pressure amplitude reaches 50.37 kPa (i.e., pressure ratio of 1.24) in the CTE. When the CTE works between room temperature and cryogenic temperature ($T_h = 300.0$ K and $T_c = 136.2$ K), pressure amplitude of 22.68 kPa is obtained, which is 4.07 times than the oscillator made by Wheatley [18] and 7.82 times than the TE made by Luck [19].

The value of the ratio $R_T = T_h/T_c$ is close to obtain the same pressure ratio (see FIGURE 9) both in CTE and HTE. A pressure ratio of 1.21 is obtained when the ratio $R_{T-CTE} = T_h/T_c = 525.5$ K/147.6 K = 3.76 in CTE and $R_{T-HTE} = T_h/T_c = 923.9$ K/287.1 K = 3.21 in HTE. The operating processes of CTE and HTE reveal that the value of R_{T-CTE}/R_{T-HTE} is almost at a constant value (ranges within 1.1-1.2) to obtain the same pressure ratio. Thus whatever the driving method is, the performance of a TE is determined by the ratio T_h/T_c . Larger T_h/T_c indicates a better performance of the TE. At lower temperatures, smaller difference of $T_h - T_c$ can lead to relatively large values of T_h/T_c , this is the reason why the performance of a TE is improved at lower gas temperatures.

CONCLUSIONS

A standing-wave TE driven by liquid nitrogen was first designed and tested. Theory

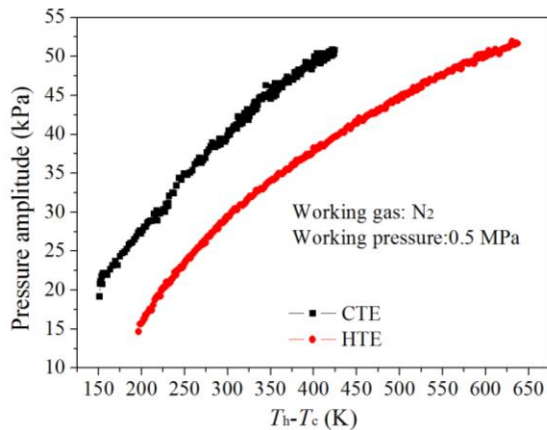


FIGURE 8. The pressure amplitude comparison in CTE and THE

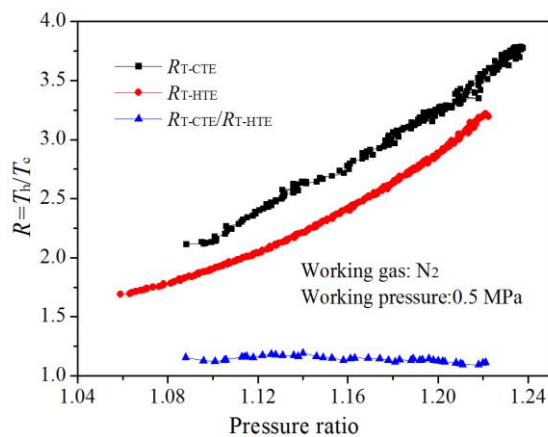


FIGURE 9. Comparison of ratio T_h/T_c in CTE and THE

analysis shows that the onset temperature difference between the hot and cold end of the stack significantly decreases when the cooler is cooled by liquid nitrogen. The TE can obtain a larger pressure amplitude with a smaller temperature difference between the hot and cold end of the stack due to changes of gas properties at the lower gas temperature. Besides, it also shows that the exergy efficiency can increase under suitable circumstance. Experiments verify the theoretical predictions. With nitrogen of 0.5 MPa as working gas, a pressure ratio of 1.21 is obtained by the driving method of CTE with a temperature difference which is 40.4% smaller compared with HTE. Pressure amplitude of 22.68 kPa is obtained when the temperatures of the hot and cold end of the stack of the CTE are at room temperature and 136.2 K, respectively. With helium of 0.63 MPa as working gas, the onset temperature difference decreases by 28.9%. The experiments show that the temperature ratio of the hot end to the cold end mainly determines the output pressure amplitude of a TE. The thermoacoustic engine driven by the cryogenics, for example, liquid nitrogen and liquefied nature gas (LNG), may be an alternative for recovering cold energy and low-grade thermal energy.

ACKNOWLEDGMENTS

The project is supported by China National Funds for Distinguished Young Scientists under contract No. 50825601 and partly by the Major State Basic Research Development Program of China under contract No. 2010CB227303. The authors thank Dr. Ray Radebaugh and Prof. de Waele for helpful discussions.

REFERENCES

1. Backhaus, S. and G.W. Swift, *Nature* **399**, pp. 335-338 (1999).
2. Adeff, J.A. and T.J. Hofler, *Journal of the Acoustical Society of America* **107(6)**, pp. L37-L42 (2000).
3. Luo, E., et al., *Chinese Science Bulletin* **50(3)**, pp. 284-286 (2005).
4. Sun, D.M., et al., *Energy Conversion and Management* **46(2)**, pp. 281-291 (2005).
5. Tang, K., et al., *Applied Physics Letters* **94(25)**, pp. 254101-1~254101-3 (2009).
6. Keesom, W.H., *Helium*, Elsevier, Amsterdam, 1942.
7. Taconis, K.W., et al., *Physica* **15(8-9)**, pp. 733-739 (1949).
8. Clement, J.R. and J. Gaffney, "Thermal oscillation in low temperature apparatus," in *Advances in Cryogenic Engineering* **1**, 1954, pp. 302-306.
9. Rott, N., *Zeitschrift für Angewandte Mathematic und Physic* **20(2)**, pp. 230-243 (1969).
10. Rott, N., *Z. Angew. Math. Phys* **24**, pp. 230-43 (1973).
11. Rott, N., "Thermoacoustics," in *Adv. Appl. Mech.* **20**, 135-175 (1980).
12. Yazaki, T., et al., *Physical Review Letters* **64(21)**, pp. 2515-2518 (1990).
13. Yazaki, T., A. Tominaga, and Y. Narahara, *Journal of low temperature physics* **41**, pp. 45-60 (1980).
14. Sugimoto, N. and D. Shimizu, *Physics of Fluids* **20(10)**, pp. 104102 (2008).
15. Shimizu, D. and N. Sugimoto, *Journal of the Physical Society of Japan* **78(9)**, pp. 4401 (2009).
16. Shimizu, D. and N. Sugimoto, *Journal of Applied Physics* **107(3)**, pp. 034910-1~034910-11 (2010).
17. T. Yazaki, A. Tominaga, and Y. Narahara, *Cryogenics* **19**, pp. 393-396 (1979).
18. Wheatley, J., et al., *American Journal of Physics* **53(2)**, pp.147-162(1985).
19. Luck, H. and C. Trepp, *Cryogenics* **32(8)**, pp. 690-697 (1992).
20. Luck, H. and C. Trepp, *Cryogenics* **32(8)**, pp. 698-702 (1992).
21. Swift, G., "Thermoacoustics: A unifying perspective for some engines and refrigerators," *Condensed Matter and Thermal Physics Group, Los Alamos National Laboratory*, 2001.
22. Ward B, Clark J, Swift G, *J Acoust Soc Am* **95**, 3671-2 (1994).