A novel heat-driven thermoacoustic natural gas liquefaction system. Part I: the impedance coupling rule between refrigerator and linear alternator

Linyu Li[a], Zhanghua Wu[b], Limin Zhang[c], Ercang Luo[d], Dai Wei[e]

[a] *University of Chinese Academy of Sciences, Beijing, China, li_linyu@qq.com*
[b] *Key Laboratory of Cryogenics, Chinese Academy of Sciences, Beijing, China, zhhwoo@mail.ipc.ac.cn*
[c] *Key Laboratory of Cryogenics, Chinese Academy of Sciences, Beijing, China, azhanglm@126.com*
[d] *Key Laboratory of Cryogenics, Chinese Academy of Sciences, Beijing, China, ecluo@mail.ipc.ac.cn*
[e] *Key Laboratory of Cryogenics, Chinese Academy of Sciences, Beijing, China, cryodw@ mail.ipc.ac.cn*

Abstract:

Nowadays, thermoacoustic heat engine is of great interest in the world, which is capable of converting external heat to acoustic power with high reliability by eliminating all moving parts and is suitable for natural gas liquefaction, solar energy and other application areas. The acoustic power can be further utilized to obtain cooling power or electric power by coupling thermoacoustic refrigerators or linear alternators with the engine, respectively. In this paper, a novel heat-driven thermoacoustic natural gas liquefaction system is proposed. Here, the linear alternator is used to not only provide a suitable phase relationship for the refrigerator to achieve a high refrigeration performance, but also recover the expansion work of the refrigerator and convert it into electricity. However, due to the complicate energy conversion mechanism between heat power, acoustic power, cooling power and electric power in the system, we study the impedance coupling rule between refrigerator and alternator first by means of simulation in this paper. For a given refrigerator, the impedance influence of the linear alternator on the refrigerator performance is investigated by adjusting equivalent inductance and load resistance of the alternator. As a result, the refrigerator can obtain a cooling power of 426.6 W at 110 K with a relative Carnot efficiency of 54.0%, while the alternator can obtain an electric power of 421.5 W with efficiency of 69.0% and an exergy efficiency of 58.7% of the unit. The operation conditions are 6.0 MPa mean pressure, 1.15 pressure ratio and 60 Hz working frequency, respectively. Since several refrigerator and alternator units can be connected with the engine, this technology may provide a new way for natural gas liquefaction.

Keywords:

Cooling and Power System, Thermoacoustic Refrigerator, Linear Alternator, Thermoacoustic Heat Engine, Natural Gas Liquefaction.

1. Introduction

With the rapid development of world economy and population, the world's energy demand is also growing dramatically. However, the greenhouse effect and a variety of emissions of harmful substances have caused great challenges to the human survival environment. In this background, natural gas has attracted considerable attention around the world as a kind of clean energy resource and chemical raw material. In recent years, the growing speed of the natural gas consumption is very high, especially in China [1]. Although most of natural gas is carried to user as gas by pipelines, the share of liquefied natural gas (LNG) is increasing to facilitate long-distance trade and bring gas from remote reserves to market. In Conventional natural gas liquefaction systems, steam turbines or internal combustion engines are used to drive the compressors to condense the refrigerants to complete the refrigeration cycles [2]. Thus, the refrigerant at evaporation temperature can absorb cooling power and LNG can be obtained. However, these systems are extremely complex and maintenance costs are very high.

After the first heat-driven thermoacoustic refrigerator was developed by Radebaugh in 1990 [3], the heat-driven thermoacoustic natural gas liquefaction system was investigated since 1994 in USA [4-

6]. In these systems, thermoacoustic heat engines, including standing-wave and traveling-wave types, were used to convert the external heat to mechanical power in the form of high-intensity sound wave. Thereby, the thermoacoustic refrigerator (TAR) could be driven by the mechanical power to achieve cooling power. In comparison with conventional natural gas liquefaction technologies, the heat-driven thermoacoustic natural gas liquefaction technology has outstanding advantages on high reliability, long life and low maintenance without any moving parts. The traveling-wave thermoacoustic heat engine (TWTAHE) can achieve higher efficiency than the standing-wave thermoacoustic heat engine, because the TWTAHE is based on the reversible thermodynamic cycle in the regenerator.

So far, three kinds of TWTAHE have been developed. The first one is the traditional TWTAHE. After about two decades proposed by Ceperley [7], the first TWTAHE was developed by Backhaus and Swift in 1999 [8, 9]. They achieved 30% thermoacoustic efficiency (comparable to 25–40% efficiency of the conventional internal combustion engine) by incorporating a feedback-inertance structure and closed resonator, which have become typical feature of traditional TWTAHE. Nevertheless, this structure made the power density very low and dissipated a lot of acoustic energy in resonators. The second one is double-acting TWTAHE. Since 2011, Luo Ercang from China proposed a double-acting process assembling TWTAHEs or traveling-wave TARs and double-acting linear motors to form a loop [10-12] that recycled the acoustic energy and improved the efficiency significantly. Nevertheless, double-acting linear motors brought severe problems with consistency that are unable to solve. Taking full advantage of traditional TWTAHE and double-acting TWTAHE, the third type of TWTAHE named acoustically resonant type TWTAHE was presented [13], which can avoid the troublesome inconsistency. In 2014, Luo Ercang et al. investigated an acoustically resonant cooling system, but the overall relative Carnot efficiency only reached 3.5% [14].Based on this, a novel heat-driven thermoacoustic natural gas liquefaction system (HDTANGLS) was proposed in this paper, the system consists of multi-stage acoustically resonant TWTAHE and several load units of TAR and linear alternator. The and Compared with traditional traveling wave TAR through mechanical structure or pipeline to recover expansion work, using the alternator will not only reduce the complexity of the structure, but also improve sound field inside the refrigerator and raise the performance of the refrigerator prominently. In addition, the expansion work out of the TAR will be converted into electricity by the alternator.In this paper, due to the complicate energy conversion mechanism between heat, acoustic power, cooling power and electric power, we study the impedance coupling relationship between TAR and alternator first. The impedance coupling relationship between the engine and the TAR and alternator unit is not included here and will be investigated in the near future.

2. System configuration

Fig. 1(a) shows the schematic of the HDTANGLS, which contains a four-stage TWTAHE and four TAR and alternator units. Actually, according to our numerical results, three to six stages are preferable for this type of system. The four-stage TWTAHE consists of four engine units, each unit contains a main ambient heat exchanger, a regenerator, a heater block, a thermal buffer tube, a secondary ambient heat exchanger and a long and thin resonance tube. The TAR and alternator unit, demonstrated in Fig. 1(b) consists of a TAR and a linear alternator. The TAR is composed of a main water cooler (MWC), a regenerator (REG), a cold end (CE), a pulse tube (PT) and a secondary water cooler (SWC). The structure parameters of the TAR are presented in Table 1. The homemade linear alternator has a dual-opposed configuration with two same linear motors to eliminate the vibration. The electrical and mechanical parameters of the motor are described as follows: 150.0 N/A transduction coefficient (τ), 1.9 Ω and 0.155 H electrical resistance (r) and inductance (L) of the winding, 75 N/mm mechanical spring stiffness (K), 1.8 kg moving mass (M), 65mm piston diameter (D), 0.526 L and 1 L front and back volume (V_f and V_b), 25 Ns/m mechanical damping coefficient (R_m). Additionally, the linear alternator has a displacement limitation of 8 mm. A rheostat (R) and capacitance (C) are connected in series with the linear alternator to serve as the electrical loads to consume the electric power generated by the alternator.

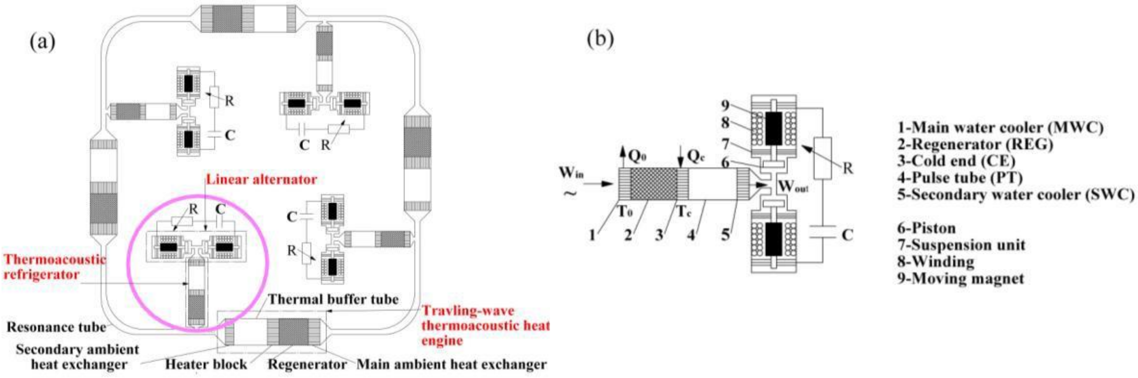

Fig. 1. (a) Schematic of the HDTANGLS*, (b) Schematic of the TAR and alternator unit.*

Table 1. Structure parameters of the TAR

	D(mm)	l(mm)	Others
Main water cooler	75	50	Finned heat exchanger with fin spacing of 0.4 mm
Regenerator	75	65	300 mesh stainless steel screen
Cold end	75	30	Finned heat exchanger with fin spacing of 0.3mm
Pulse tube	50	125	/
Secondary water cooler	50	10	40 mesh copper screen

3. Simulation results and discussion

The numerical simulation is performed using DeltaEC program [15, 16], which is based on the traditional thermoacoustic theory. Firstly, the working mechanism of the TAR is introduced by the temperature and power distributions. Then, the influences of the alternator parameters on the TAR performance are investigated, including the electrical resistance and equivalent inductance. By analyzing the influences of these two parameters on the acoustic field of the TAR, the optimum working parameters can be obtained.

3.1. Working mechanism

In order to further understand the thermodynamic characteristics of the TAR and alternator unit, axial distributions of key parameters are presented in Figs. 2 to 3. In these figures, the X axis begins at the main water cooler of the TAR, and then goes right as shown in Fig. 1(b). Because lumped parameter method of the alternator is used in the simulation, the X axis does not include the alternator length. The load resistance and the equivalent inductance are set to 60 Ω and 0 H, respectively. Equivalent inductance, described by $L'=L-1/\omega^2C$, means a small capacitance connected in the circuit to control the impedance of the alternator. Other operation conditions are a mean pressure of 6.0 MPa, a pressure ratio of 1.15 and a working frequency of 60 Hz, respectively.

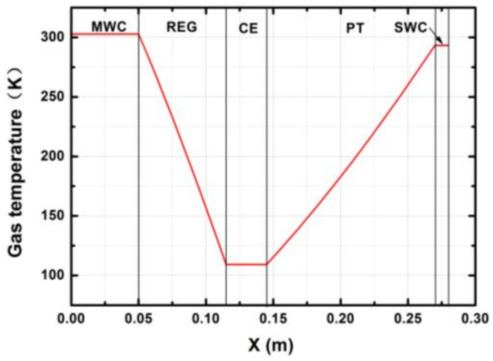

Fig. 2. Axial distribution of gas temperature.

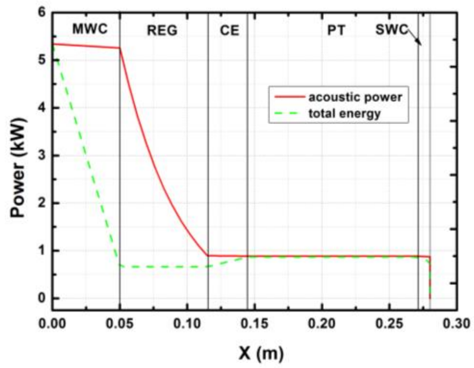

Fig. 3. Axial distributions of acoustic power and total energy.

Figs. 2 to 3 demonstrate the axial distribution of gas temperature, acoustic power and total energy. The total energy is defined as the sum of acoustic power and heat exchange between the working gas and solid wall. From Fig. 2, the gas temperature decreases in the regenerator from water cooling temperature to the refrigeration temperature of 110 K, then it increases back in the pulse tube. From the distributions of acoustic power and total energy in Fig. 3, about 5.34 kW acoustic power is input to the TAR. In the main water cooler, the acoustic power is slightly dissipated about 84.6W and the total energy decreases from 5.34 kW to 0.66 kW due to the heat rejected to the environment. The regenerator consumes 4.36 kW acoustic power to pump 0.2 kW cooling power from the cold end. In the secondary water cooler, very little heat is released and the total energy is slightly decreased. Lastly, about 0.87 kW acoustic power out of the TAR is converted into electricity by the alternator, which is demonstrated by the power drop because of lumped parameter model of the alternator. The computational output electric power is 0.79 kW with efficiency of 90.8%.The output electric power can be calculated by

$$W_e = I^2 R / 2 , \quad (1)$$

Where I is magnitude of current amplitude, and the alternator efficiency is defined as

$$\eta = W_e / W_{out} . \quad (2)$$

3.2. Parameter optimization

For a given TAR, the performance is determined by the alternator impedance. It is important to investigate the influences of the alternator parameters to reveal the impedance coupling relationship. According to the control equations of linear alternator [16], the acoustic impedance of the alternator can be calculated by

$$Z = \frac{1}{A^2}\left[R_m + i(\omega M - \frac{K}{\omega}) + \frac{\tau^2}{R + r + i(\omega L - 1/\omega C)} \right]. \quad (3)$$

In these parameters, only the load resistance and the capacitance can be easily changed. So, we study their influences on the TAR performance.Figs. 4 to 5 demonstrate the influence of the equivalent inductance on the phase angle and performance of the TAR at different specific load resistors. The phase difference of volume flow rate between inlet and outlet of the TAR is vital to the TAR performance. In the acoustically resonant thermoacoustic engines, the phase difference is -120° for three-cylinder system and -90° for four-cylinder system [17]. As demonstrated in Fig. 4, the equivalent inductance can greatly change the phase angle of the TAR especially at low load resistance, and low load resistance can achieve -90° phase difference at specific equivalent inductances. According to Fig. 5, the cooling power and relative Carnot efficiency of the TAR can reach an optimum area at large phase angle difference. The relative Carnot efficiency is defined as

$$\eta_{relative} = \frac{Q_c}{W_{in} - W_{out}} \bigg/ \frac{T_c}{T_0 - T_c} . \tag{4}$$

However, lower load resistance can obtain a higher efficiency but lower cooling capacity. So, one should balance between the efficiency and power density by choosing proper impedance value of the alternator in the system design. In Fig. 6, the alternator performance is presented. It seems that the alternator prefers the zero equivalent inductance and a proper load resistance to reach highest efficiency and smallest piston displacement. Hence, the choice of load resistance should be compromised. The input acoustic power of the TAR and alternator unit demonstrated in Fig. 7 is an important condition in matching the unit with the TWTAHE in the future. Taking the power output capability of the engine into consideration, the engine may provide about 2 kW acoustic power. From Fig. 7, the highest exergy efficiency can be obtained at large phase angle difference, which is similar to the relative Carnot efficiency. Therefore, the optimum results are a cooling power of 426.6 W at 110 K with a relative Carnot efficiency of 54.0%, an electric power of 421.5 W with efficiency of 69.0% and an exergy efficiency of 58.7% with resistance of 30 Ω and the equivalent inductance of -0.3 H. The exergy efficiency is used to evaluate the performance of the unit, which is defined as

$$\eta_e = \left[\left(T_0 / T_c - 1 \right) Q_c + W_e \right] / W_{in} . \tag{5}$$

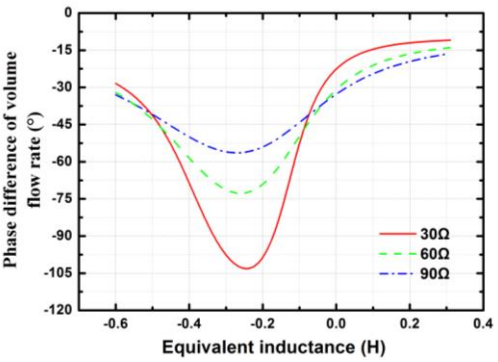

Fig. 4. The phase difference of volume flow rate versus equivalent inductance with different resistors.

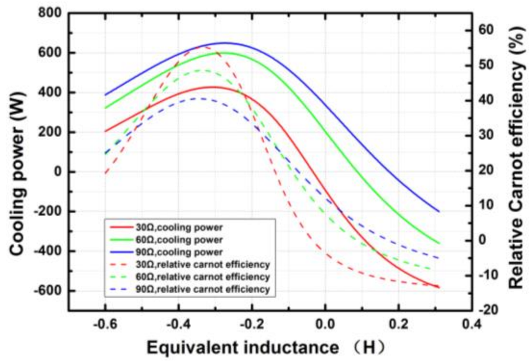

Fig. 5. Cooling power and relative Carnot efficiency versus equivalent inductance with different resistors.

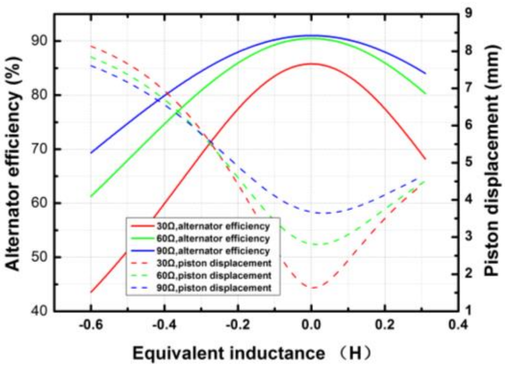

Fig. 6. Alternator efficiency and piston displacement versus equivalent inductance with different resistors.

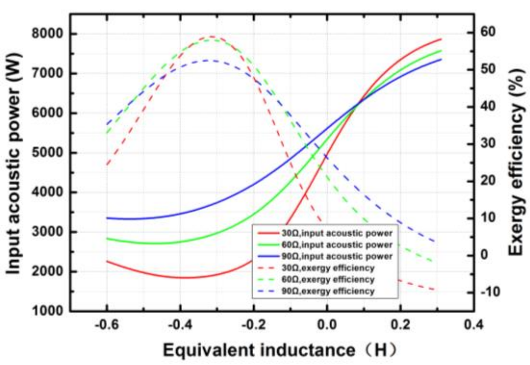

Fig. 7. Input acoustic power and exergy efficiency versus equivalent inductance with different resistors.

4. Conclusions

In this paper, a novel heat-driven thermoacoustic natural gas liquefied system is proposed by our group. It uses a multi-stage TWTAHE to convert external heat to acoustic power, and then drive a thermoacoustic TAR and linear alternator unit to produce cooling power and electric power. The alternator is used to not only provide a suitable phase angle for the TAR to achieve a high performance, but also convert the expansion work out of the TAR to electricity. Here, the thermoacoustic TAR and linear alternator unit is numerically investigated. Firstly, distributions of gas temperature, acoustic power and total energy are presented to understand the energy conversion characteristic of the unit. Then, the simulations are performed to analyze the influence of equivalent inductance and load resistance of the alternator on the TAR performance, which reveals the impedance coupling relationship between the TAR and the alternator. As a result, the TAR can obtain a cooling power of 426.6 W at 110 K with a relative Carnot efficiency of 54.0%, the alternator can obtain an electric power of 421.5 W with efficiency of 69.0% and an exergy efficiency of 58.7% of the unit. In the near future, the experimental work will be performed and reported. Additionally, the impedance coupling mechanism between the TWTAHE and the cooling and power unit will be investigated in the next paper.

Acknowledgments

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References

[1] Zhang Kang. Natural gas supply-demand situation and prospect in China. Natural Gas Industry B 2014; 1 (1): 103-112.

[2] Mokhatab S, Mak J Y, Valappil J V, et al. Handbook of Liquefied Natural Gas. Gulf Professional Publishing, 2013.

[3] R. Radebaugh, K. M. McDermott, G. W. Swift and R. A. Martin. Development of a thermoacoustically driven orifice pulse tube refrigerator. In Proceedings of the Interagency Meeting on Cryocoolers, 1990, Plymouth, MA, page 205-220.

[4] Swift GW. Thermoacoustic natural gas liquefier. DOE Natural Gas Conference, Houston. 1997. 1-5.

[5] Arman B, Wollan JJ, Swift GW, et al. Thermoacoustic natural gas liquefiers and recent developments. In: Chen, G B, Hebral, B, and Chen, G M. Cryogenic and Refrigeration Proceedings of ICCR. Hang Zhou: International Academic Publisher and World Publishing Corporation, 2003. 123-127.

[6] Arman B, Wollan JJ, Kotsubo V, et al. Operation of thermoacoustic Stirling heat engine driven large multiple pulse tube refrigerator. In: Ross, R G Jr. Cryocooler 13. New York: Springer Science and Business Media Inc., 2004. 181-187.

[7] Ceperley P. A pistonless stirling engine – the traveling-wave heat engine. Acoustical Soc Am 1979; 66: 1508–13.

[8] Backhaus S, Swift G. A thermoacoustic stirling heat engine. Nature 1999; 399: 335–8.

[9] S.Backhaus, G.W. Swift. A thermoacoustic-Stirling heat engine: Detailed Study. J.Acoust. Soc.Am., 2000; 107(6): 3148-66

[10] Guoyao Yu, Ercang Luo, Zhanghua Wu et al. Investigation on a three-cylinder thermoacoustic double-acting electric generator. International Conference on Applied Energy, 2012. Suzhou, China.

[11] Zhanghua Wu, Guoyao Yu, Wei Dai, Ercang Luo, Limin Zhang. Design and test of a 3 kW double-acting thermoacoustic electrical generator. International Conference on Applied Energy, 2013. Pretoria, South Africa.

[12] J.Y. Hu, E.C. Luo, L.M. Zhang, X.T. Wang, W. Dai. A double-acting thermoacoustic cryocooler for high temperature superconducting electric power grids. Applied Energy, 2013; 112:1166-70.

[13] De Block K. Novel 4-stage Traveling Wave Thermoacoustic Power Generator. Proceedings of ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels, 2010, Montreal, Canada, 2-4 August.

[14] Tong Huan, Hu Jianying, Zhang Limin, Luo Ercang. The Experimental Study of an Acoustically Resonant Cooling System. 25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014.

[15] Ward B, Clark J, Swift G. Design environment for low-amplitude thermoacoustic energy conversion, DELTAEC Version 6.2 Users Guide. Los Alamos, the US: Los Alamos National Laboratory; 2008.

[16] Swift GW. Thermoacoustics: a unifying perspective for some engines and TARs. *AIP Press*: New York, 2002.

[17] Berchowitz D, Kwon Y. Multiple-cylinder, free piston, alpha configured Stirling engines and heat pumps with stepped pistons. United States Patent 2007; 7171811B1.