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MULTI-STAGE TRAVELING-WAVE THERMOACOUSTIC POWER GENERATION SYSTEM UTILIZING LNG COLD EXERGY AND LOW-TEMPERATURE WASTE HEAT

Honghao Pan[1 2], Daming Sun[1 2], Jie Zhang [1 2]

1 Institute of Refrigeration and Cryogenics, Zhejiang University, Hangzhou 310027, PR China

2 Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Hangzhou 310027, PR China

ABSTRACT

As one of the cleanest energy source, liquefied natural gas(LNG) plays an essential part in the world energy market. This study proposes to utilize the LNG cold exergy and low-temperature waste heat with a three-stage traveling-wave thermoacoustic engine(TWTAE) coupled with linear alternators(LA). Numerical simulation is conducted to optimize the performance of this system. The effect of multiple factors of both the looped thermoacoustic engine(TAE) and the LA has been investigated. The three-stage traveling-wave thermoacoustic electric generator (TWTAG) operating with 4 MPa Helium under a temperature difference of 110-500 K is able to extract 15 kW acoustic power while the output electric power is nearly 13 kW. The overall exergy-to-acoustic efficiency is 44.2% while the heat-to-electric efficiency is nearly 40%.

Keywords: thermoacoustic; power generator; traveling wave; cold exergy; liquefied natural gas.

1. INTRODUCTION

In the past few years, the production capacity of LNG has risen rapidly. It is estimated that the consumption of natural gas will be ranked in second place among primary energy by 2030[1]. Nearly one-third of the total natural gas transaction volume is transported in the form of LNG, which needs to be revalorized in the local LNG gasification station before put into utilization. 830~860 kJ/kg cold exergy would be released during this process.

Among all of the LNG cold exergy recovery methods, power generation might be the most promising way to achieve large-scale engineering application. The earliest power generation method utilizing cold exergy mainly includes direct expansion, Rankine and gas cycles. Up to now, different types of improved compound energy cycle projects and complex multi-stage combined power generation methods are still emerging, and their performance is continuously improving. But affected by their high system complexity and substantial initial investment, quite a part of the projects mentioned earlier could hardly survive the low economic benefits and long investment recovery cycles.

Stirling cycle is another option practical for the cold exergy utilization. With the highest theoretical efficiency, an ideal Stirling cycle containing two isothermal process matches perfectly with the LNG gasification process. So far, the Stirling cycle's promising prospect in the cold recovery field has been proved by pieces of research from both theoretical and experimental aspects[2-4]. However, Stirling engines still suffer from the sealing and lubrication problem of the moving parts working under extreme temperatures, which significantly adds to its manufacturing difficulty.

As a particular variant of Stirling engine, thermoacoustic engine(TAE) inherited the merits of high efficiency and reliability but avoided the defect of difficult manufacture by removing all moving parts. In recent years, the experimental research over relatively large-scale TAEs has adequately demonstrated that the technology of thermoacoustic power generation has reached a critical period of engineering application[5].

Driven by the temperature gradient along the regenerator(REG), a TAE could also work under cryogenic conditions. Verification of its feasibility has already been carried out by a few theoretical studies [6-7]. However, the working characteristics and design principle of the cold-driven TAE differs much from its heat-driven counterparts and yet still needs to be further discussed.

In this paper, a three-stage looped TWTAG system is proposed and optimized. Driven by both cold and heat exergy, this novel thermoacoustic system has the potential of reaching a much higher performance than its heat-driven counterpart with the same temperature difference along regenerator. The influence of multiple factors in both TAE circuit and the acoustic load is also investigated by numerical analysis for the guidance of further studies.

2. SYSTEM CONFIGURATION

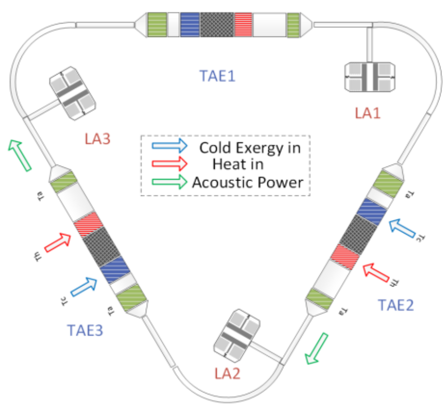


Fig 1 Schematic of the looped three-stage traveling-wave thermoacoustic generator system

The three-stage TWTAG is composed of 3 similar TAE units and 3 pairs of LA connected by the long hollow resonance tube of relatively small cross-section area. Each TAE consists of two ambient-temperature heat exchanger(AHX), one hot-end heat exchanger(HHX), one cold-end heat exchanger(CHX), two thermal-buffer tube(TBT) and one REG.

All of the HXs installed inside the system are shell-tube heat exchangers, in which the working fluids flow inside the tube while the LNG flows into the CHX and vaporizes to NG in the shell side. Meanwhile, the HHX is heated by the media fluid carrying waste heat while the cooling water flows through the 2 AHXs. Two TBTs are installed for the isolation of the extreme temperature to minimize energy loss. Both elastic membranes and flow straighteners are applied to suppress the harmful streaming phenomena.

3. SIMULATION METHOD

The numerical simulation is conducted by using the software DeltaEC, which was based on the classic thermoacoustic theory developed by Rott, Xiao, and Swift[8]. DeltaEC provides a series of segments corresponding to the physical components inside thermoacoustic systems and employs the shooting method to meet the boundary conditions. Its accuracy has been verified by a large amount of previous experimental studies[9-10] and is currently widely used as reliable guidance for the study in the thermoacoustic field.

The three-stage thermoacoustic engine is designed to utilize the LNG cold exergy and low-temperature waste heat. Thus, the solid temperature of the HHX, CHX, and AHX is set to be 500K, 110K, and 300K, respectively. 4 MPa Helium is applied as the working fluid.

4. RESULTS AND DISCUSSION

4.1 Optimization of the regenerator

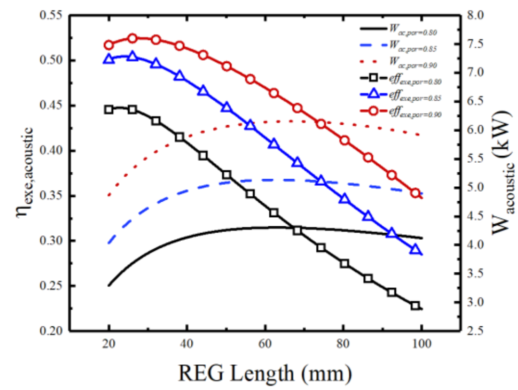


Fig 2 The effect of REG length and porosity on the system performance

Known as the core component of TAE, a proper REG is critical to the overall system performance. In this section, a few key parameters of REG including length, porosity, and hydraulic radius is optimized and discussed separately.

According to the simulation result shown in Fig.2, the optimum performance is achieved with a porosity of 0.9. A higher porosity usually leads to a lower flow viscosity loss, but it might be unwise to lift the porosity blindly in case the heat capacity of the porous media might be insufficient.

The performance curves of the TAE with different hydraulic radius r_h of the REG are displayed in Fig 3. It is obvious that the system performance got worse when r_h is deliberately decreased from 45μm for the cold-driven mode. The selection of r_h under cryogenic working condition shows an unexpected characteristic. The optimum radius seems to be nearly one δ_k while it is always lower than 1/3 δ_k for a better heat transfer condition according to former experience gained from previous studies based on heat-driven thermoacoustic systems.

4.2 Impedance matching between TAE and LA

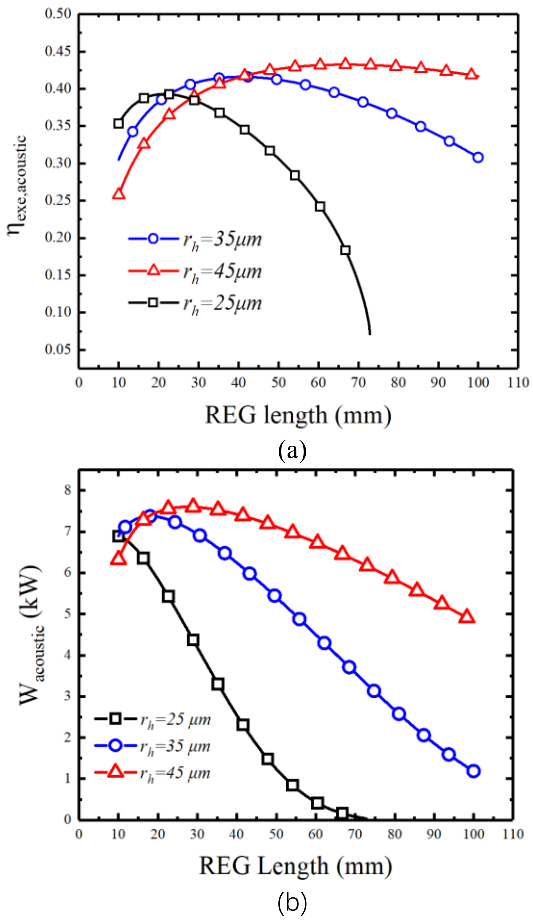


Fig 3 (a)Exergy efficiency of acoustic and (b) acoustic power output of one of three stages vary with hydraulic radius in different REG length

It is known that the impedance matching between TAE and LA has a significant impact on the overall system performance. Since the output impedance of the TAE is already determined after the optimization process, the impedance equilibrium state could only be achieved by the properly adjusted load-side parameters including both mechanical and electrical parameters.

Among them, the mechanical parameters mainly affect the load impedance by changing the resonant frequency of LA, which is decided by multiple parameters including the moving mass M, the spring stiffness K, and the back volume V_b.

In 2017, Wang et al. [6] have already attempted to match the frequency by adjusting the back volume of LAs. This method could be impractical since V_b could easily get out of range when a compact structure is expected. Therefore, in this study, the Spring blade stiffness is set as a variable while other parameters fixed at desirable value.

According to the simulation result, as is shown in Fig.4(b), the resonant frequency of LA should be nearly 10 Hz lower than the system operating frequency in this case, spring blades with the stiffness of 76 kN/m should be applied in the LA for the optimum overall performance.

Compared with the mechanical parameters of LA, the electrical parameters on the load-side circuit including capacity and resistance are obviously more adjustable in real-life projects. After the conventional optimization process commonly applied on thermoacoustic systems, the optimum power output of 7.8 kW electric power and 8.6 kW acoustic power could be obtained with a capacity of 30μF. And after taking all of the factors into consideration, with the electric capacity $C_{load} = 50$ μF, electric resistance $R_{load} = 48$ Ω, the final scheme sacrificed a little power output for the highest exergy efficiency of 37%.

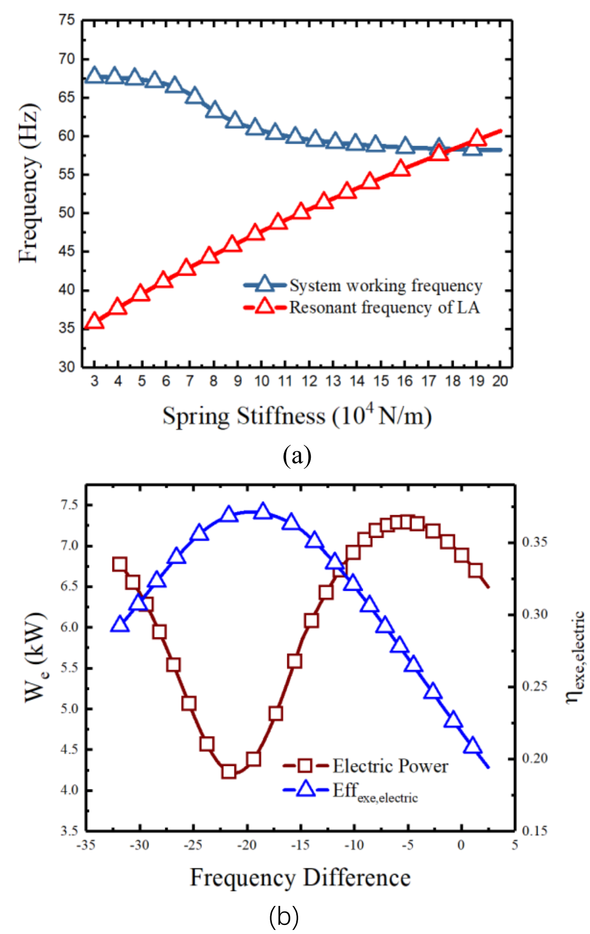
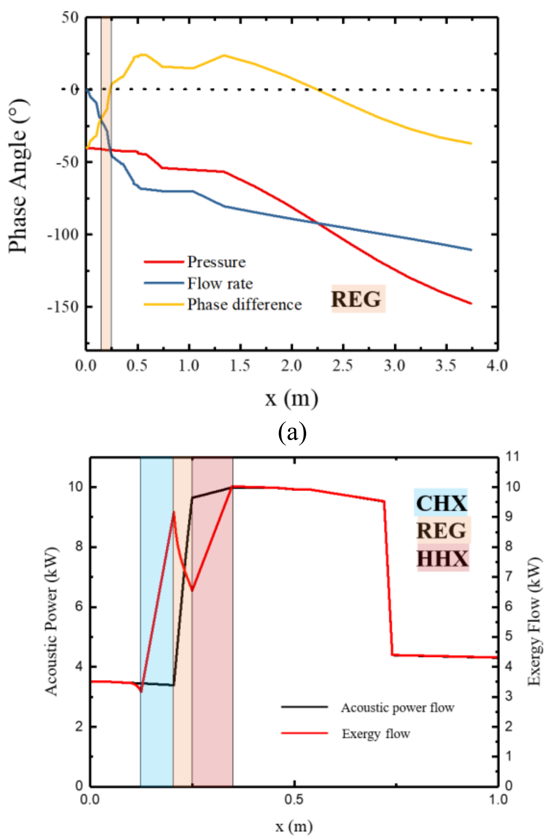


Fig 4 (a)Working frequency and LA's resonant frequency with different Spring stiffness;(b)System performance with the difference between LA's resonant frequency and system working frequency

4.3 *Distribution of the acoustic fields*

Distribution of a few key parameters including phase angle, acoustic power, and exergy flow is further investigated. As is shown in Fig 5(a), the zero-frequency difference representing the pure traveling-wave acoustic field obtained in the REG is a good sign of a qualified-designed TAE which agrees well with the traditional design principle. And according to Fig 5(b), hot and cold exergy enters the system through HHX and CHX separately. And as the core segment where the energy conversion happens, REG is also responsible for most of the exergy loss in the whole circuit.



(b)

Fig 5 (a)Phase of pressure oscillation and flow rate; (b) Acoustic power and exergy flow along the loop

4.4 Conclusions

According to the study, the design principle of the regenerator and resonant tube for a cold-driven thermoacoustic power generator could be very different from the traditional heat-driven thermoacoustic systems in some aspects which are obviously reflected in the optimization process of REG parameters.

Both mechanical and electrical parameters of the LA is important to achieve the impedance balance between TAE and the load side. Adjusting the spring blade stiffness could be more flexible and practical compared with other mechanical parameters.

The optimized system operates with 4 MPa Helium under 110-500 K is capable of generating 13 kW electric power. With the efficiency far more beyond the reach of its heat-driven counterpart, the cryogenic TWTAG shows impressive potential in the field of cold recovery.

ACKNOWLEDGMENT

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