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# A novel heat-driven thermoacoustic natural gas liquefaction system. Part I: Coupling between refrigerator and linear motor☆

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ABSTRACT

Nowadays, heat-driven thermoacoustic Stirling refrigerator is of great interest in the world, which utilizes thermoacoustic heat engine to drive thermoacoustic Stirling refrigerator with high reliability and simplicity. This system is suitable for natural gas liquefaction by burning a small amount of natural gas to liquefy the rest. In this paper, a heat-driven thermoacoustic Stirling refrigerator with linear motor phase adjuster is proposed. The linear motor is used to not only provide a suitable acoustic field for the refrigerator to achieve a high performance but also convert the expansion work into electricity. Thus, the system efficiency can be greatly improved. Due to the complicated energy conversion mechanism between heat, acoustic work, cooling power and electric power in the system, here we only try to investigate the coupling relationship between refrigerator and linear motor by adjusting load resistance and equivalent inductance. According to the simulation, optimum results of a cooling power of 463.1 W at 110 K with relative Carnot efficiency of 31.3%, an electric power of 553.7 W and a total exergy efficiency of 53.7% are achieved. Since several refrigerator and motor units are used in this system, this technology may provide a new way for natural gas liquefaction.



## 1. Introduction

With the rapid development of the 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 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 the conventional natural gas liquefaction systems, the steam turbines, gas turbines or internal combustion engines are used to drive the compressors and force the refrigerants to complete refrigeration cycles and liquefy natural gas. To date, three basic refrigeration cycles are mainly employed in the LNG industrial production, they are cascade cycle, mixed refrigerant cycle and gas expander cycle, respectively. In those cycles, Joule-Thomson valves and expanders are used to provide cooling power and liquefy the natural gas [2]. However, all these systems have extremely complex structures and require high maintenance costs.

Heat-driven thermoacoustic Stirling refrigerator (HDTASR) is a new machine capable of producing cooling power at low temperature from thermal energy. The HDTASRs use thermoacoustic heat engines to drive thermoacoustic Stirling refrigerators. Both the engines and the refrigerators are based on the thermoacoustic effect, which happens between the working gas and solid wall converting heat into acoustic work in the engine or pumping heat from low temperature to high temperature in the refrigerator. Composed of pipeline, porous medium and heat exchangers, the HDTASRs have outstanding advantages on structural simplicity and reliability. The first HDTASR was developed by Radebaugh et al. in 1990 [3], they used a standing-wave thermoacoustic heat engine to drive a thermoacoustic Stirling refrigerators (TASR) with an orifice-

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**Nomenclature**

| | |
|---|---|
| $A$ | cross sectional area of flow channel ($m^2$) |
| $A_s$ | cross sectional area of solid ($m^2$) |
| $c_p$ | isobaric heat capacity per unit mass (J/kg K) |
| D | diameter (mm) |
| $f$ | frequency (Hz) |
| $f_k$ | spatially averaged thermal function |
| $f_v$ | spatially averaged viscous function |
| gpd | gallon per day |
| H | total energy power (W) |
| I | current (A) |
| Im[] | imaginary part of complex number |
| i | imaginary unit |
| K | spring stiffness (N/m) |
| $k$ | thermal conductivity of gas (W/m.K) |
| $k_s$ | thermal conductivity of solid (W/m.K) |
| L | electrical inductance (H) |
| l | length (m) |
| M | moving mass (kg) |
| $P_m$ | mean pressure (Pa) |
| p | pressure amplitude (Pa) |
| q | heat input per unit length (W/m) |
| R | load resistance (Ω) |
| Re[] | real part of complex number |
| $R_m$ | mechanical damping coefficient (N.s/m) |
| r | resistance of the winding (Ω) |
| T | temperature (K) |
| U | volume velocity ($m^3$/s) |
| $V_b$ | back space volume ($m^3$) |
| $V_f$ | front space volume ($m^3$) |
| $W_a$ | acoustic work (W) |
| $W_{ain}$ | input acoustic work (W) |
| $W_{aout}$ | output acoustic work (W) |
| Z | impedance (Pa. s /$m^3$) |
| γ | specific heat ratio |
| ρ | gas density (kg/$m^3$) |
| σ | Prandtl number |
| τ | transduction coefficient (N/A) |
| ω | angular frequency (rad/s) |
| \| \| | magnitude of complex number |
| * | conjugation of complex number |

reservoir type phase adjuster and achieved a lowest temperature of 90 K. After the first thermoacoustic Stirling heat engine (TASHE) was developed by Backhaus and Swift in 1999 [4,5], more works have been done on the HDTASR system with TASHE because of a higher efficiency than the standing-wave thermoacoustic heat engine. So far, the HDTASR can achieve cooling capacity at room temperature [6], liquid nitrogen temperature [7], even liquid hydrogen temperature [8].

About twenty years ago, researchers began to realize that the HDTASR was very suitable for the application of natural gas liquefaction, which can burn a part of natural gas to liquefy the rest of it. From 1994 to 1997, Swift et al. developed a natural gas liquefaction system by using a standing-wave thermoacoustic heat engine to drive a TASR with an orifice-reservoir phase adjuster [9]. They achieved a cooling power of 2 kW at −140 °C, which represents a liquefaction rate of 140 gpd of LNG. From 1999, they built another natural gas liquefaction system with a cooling capacity of 7 kW at 120 K (i.e. a liquefaction capacity of 500 gpd of LNG) [10]. In this system, a TASHE was utilized to drive three TASRs with an inertance-reservoir phase adjuster, the overall system efficiency should yield liquefaction of 65% of a natural-gas stream by burning 35%. In 2014, Kees de Block tested a HDTASR with a multi-stage TASHE and a TASR supplied by Qdrive with an inertance-reservoir phase adjuster [11], it achieved a cold head temperature of −160 °C with a heating temperature below 300 °C [12]. In order to increase the power rate, Luo et al. designed a HDTASR operating at the LNG temperature range in 2015 [13], which consisted of a three-stage TASHE and three TASRs with inertance-reservoir phase adjusters. In the experiments, a maximum total cooling capacity of 1.20 kW at 130 K was achieved with a total exergy efficiency of 8%, which is equal to about 25% of natural gas burned to liquefy the remaining 75%. In all above-mentioned systems, the overall efficiency was lower than that of conventional natural gas liquefaction systems. The main reason is that the phase adjusters used to control the phase angle between the pressure wave and velocity oscillation of the TASR were crucial to achieve a good cooling performance. However, the expansion work, usually much higher than the cooling power, was dissipated into heat in the phase adjusters, which resulted in low efficiency and a cooling requirement of the phase adjusters especially for large power circumstance. Thus, recovery of the expansion work seems very important. As early as 1999, Swift et al. realized this problem and proposed a loop configuration TASR with an inertance-compliance phase adjuster to recover the expansion work [14]. Similar efforts have been done by Luo et al. [6]. However, due to the high cooling temperature and the coupling difficulty with the engine, the obtained cooling performances were still not encouraging for LNG application. Here, we propose a novel HDTASR for natural gas liquefaction, which consists of a multi-stage TASHE and several TASRs with linear motor phase adjusters. The linear motor can not only provide a suitable phase angle required by a good operation of the TASR, but also convert the expansion work into electricity. Thus, the efficiency of the whole system can be greatly improved. It is well known that the linear motor technology has matured for decades and has been widely used in cryocooler systems even for space applications. Thus, the combination of the TASR and the linear motor can provide both high reliability and efficiency. Furthermore, this system can provide both cooling power and electric power at the same time from thermal energy, which may be useful for off-grid natural gas liquefaction applications.

In this paper, due to the complicated energy conversion mechanism between heat, acoustic work, cooling power and electric power, we only study the coupling relationship between TASR and the linear motor. The coupling relationship between the engine and the TASR is not included here and will be investigated and reported in the future.

## 2. System configuration

Fig. 1(a) shows the schematic of our HDTASR, which contains a four-stage TASHE and four TASR and linear motor units. Actually, according to our numerical results, three to six stages are preferable for this type of system. The four-stage TASHE 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 slim resonance tube. The engine can convert

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