International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: 1157

INVESTIGATION ON HEAT-DRIVEN THERMOACOUSTIC NATURAL GAS LIQUEFACTION TECHNOLOGY

Zhanghua Wu[1], Minyu Hou[1, 2], Limin Zhang[1], Jianying Hu[1], Ercang Luo1[*]

1 Key Laboratory of Cryogenics, Chinese Academy of Sciences

2 University of Chinese Academy of Sciences

ABSTRACT

Nowadays, natural gas is one of the most important energy resources around the world. The natural gas is always liquefied for distant transportation. Thus, the natural gas liquefaction technologies are of great importance. In this paper, a heat-driven thermoacoustic refrigerator is introduced for natural gas liquefaction application, which consists of a thermoacoustic Stirling heat engine, a thermoacoustic refrigerator and a linear alternator. The engine can convert heat from burning a small amount of natural gas to acoustic work, which drives the refrigerator to produce cooling power at desired temperature. The linear alternator provides a suitable working impedance of the refrigerator and convert the expansion acoustic work of the refrigerator to electricity. This electrical power can be used to power the pump, fan and other equipment to perform the liquefaction process. According to the simulation, a maximum cooling capacity of 340 W @ 110 K for one unit was obtained with 213 W electrical power. And the maximum exergy efficiency combined cooling and power of 21% could be achieved comparing that of 12.7% without electricity.

Keywords: natural gas, liquefaction technology, thermoacoustic Stirling heat engine, thermoacoustic refrigerator, linear alternator

NONMENCLATURE

Abbreviations	
HDTAR	heat-driven thermoacoustic refrigerator
TAHE	thermoacoustic heat engine
TAR	thermoacoustic refrigerator
MAHX	main ambient heat exchanger
RGE	regenerator
HB	heater block
TBT	thermal buffer tube
SAHX	secondary ambient heat exchanger
RT	resonance tube
CE	cold end
Symbols	
A	cross sectional area of piston (m^2)
C	load capacitance (μF)
D	diameter (mm)
i	imaginary unit
K	spring stiffness (N/m)
L	electrical inductance (H)
l	length (m)
M	moving mass (kg)
Q_c	cooling capacity (W)
Q_h	heating power (W)
R	load resistance (Ω)
R_m	mechanical damping coefficient (N.s/m)
r	resistance of the winding (Ω)
η_{ex}	exergy efficiency
τ	transduction coefficient (N/A)
ω	angular frequency (rad/s)

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 significant 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]. So far, the consumption share of liquefied natural gas (LNG) is almost half of the total consumption. 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 [2]. However, all these systems have extremely complex structures and require much maintenance.

Heat-driven thermoacoustic refrigerator (HDTAR) is capable of liquefying natural gas by burning a small amount of it. HDTAR uses thermoacoustic heat engines (TAHE) to drive thermoacoustic refrigerators (TAR). 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. After the first HDTAR was developed in 1990 [3], great achievements have been made at room temperature [4], liquid nitrogen temperature [5], even liquid hydrogen temperature [6].

The first natural gas liquefaction system was developed from 1994 to 1997 by using a standing-wave type TAHE to drive a TAR [7]. A cooling power of 2 kW at -140°C is achieved, which represents a liquefaction rate of 140 gpd of LNG. In 1999, another natural gas liquefaction system with a cooling capacity of 7 kW at 120 K was built [8]. In this system, a traveling-wave type TAHE was utilized to drive three TARs. In 2014, Kees de Block tested a HDTAR with a multi-unit traveling-wave TAHE and a TAR [9], it achieved a cold head temperature of -160°C with a heating temperature below 300°C [10]. In order to increase the power rate, Luo et al. designed a HDTAR, which consisted of a three-stage traveling-wave TAHE and three TARs [11]. 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 those HDTARs, only cooling power was obtained. However, electrical power is also required to power the pumps and fans for system operation. Similar to the HDTAR, the heat-driven Thermoacoustic power generation systems have been separately investigated by using TAHE and linear alternator to convert thermal energy to electricity [12-15]. How to combine these two systems and meet the requirement of the natural gas liquefication is a big challenge.

In this paper, a new heat-driven thermoacoustic natural gas liquefaction system is introduced, which used a three-unit traveling-wave TAHE, three TARs and three alternators. The alternator is connected at the out of the TAR and can not only provide a suitable working phase condition for the TAR, but also convert the expansion work out of the TAR into electricity. Thus, the system can output the cooling power and electrical power and can operate independently.

2. SYSTEM CONFIGURATION

Fig 1 shows the schematic of the HDTAR, which contains a three-unit traveling-wave TAHE and three TARs and three linear alternators. The three-unit TAHE consists of three engine units, each unit contains a main ambient heat exchanger (MAHX), a regenerator (RGE), a heater block (HB), a thermal buffer tube (TBT), a secondary ambient heat exchanger (SAHX) and a slim resonance tube (RT). The engine converts the heating power into the acoustic work to drive the TAR. According to our simulation, three to six units are preferable for this type of engine. The TAR is composed of a MAHX, a RGE, a cold end (CE), a TBT and a SAHX. The TAR is capable of consuming the acoustic work to pump heat from low temperature to high temperature, thus cooling power can be obtained at the expected temperature. The thermal buffer tubes of the TAHE and TAR are used to isolate the cold or hot end from ambient temperature and avoid other components working within a low or high temperature environment.

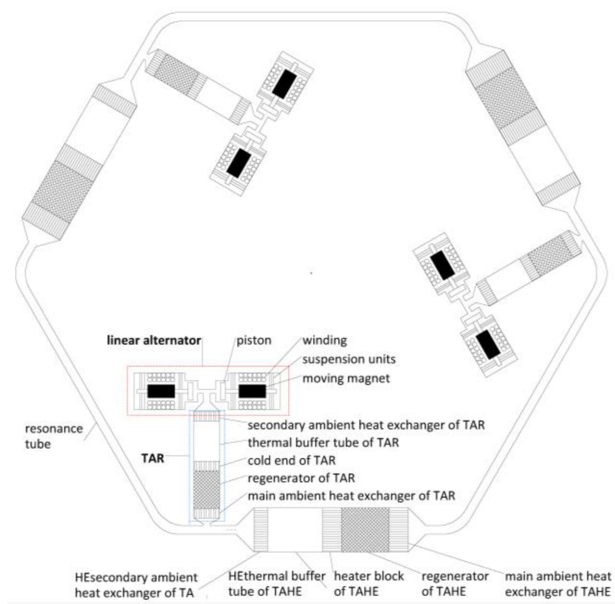

Fig 1 Schematic of our HDTAR

The structure parameters of the system are presented in Table 1. The homemade linear alternator has a dual-opposed configuration with two same motors to eliminate the vibration. The mechanical and electrical parameters of one motor are presented in Table 2. A load resistance and a capacitance are connected in series with the linear alternator to control the acoustic condition of the TAR and consume the electric power generated by the alternator.

Table 1 Structure parameters of the HDTAR

	TAHE		TAR	
	D(mm)	l(mm)	D(mm)	l(mm)
MAHX	80	60	80	64
REG	80	60	80	70
HB	80	80	/	/
TBT	80	400	37	150
SAHX	80	40	37	10
RT	20	2250	/	/
CE	/	/	80	30

Table 2 Main parameters of one motor

D (mm)	*M* (kg)	*K* (kN/m)	R_m (N.s/m)	*τ* (N/A)	*L* (H)	*r* (Ω)
65	1.8	75	25	150	0.155	1.9

3. SIMULATION MODEL

The numerical simulation is performed by using DeltaEC program [16], which is based on cross-sectional area averaged and one-dimensional model. The program provides a series of modules to simulate different thermoacoustic components, such as HX (heat exchanger), STKSCREEN (regenerator), STKDUCT (pulse tube) and so on. The geometry parameters of thermoacoustic components are given by the user. And the thermophysical properties of gas and solid are provided by the program itself. A shooting method is utilized to satisfy a variety of boundary conditions set by the users.

According to the control equations of the linear alternator, the acoustic impedance can be described as

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

The resistance and capacitance of the linear alternator can be adjusted to change the impedance of the linear alternator. Thus, the performance of the TAR and TAHE will be greatly influenced.

The exergy efficiency of the HDTAR without and with electrical power are identified respectively as

$$\eta_{ex1} = \left[\left(\frac{T_0}{T_c} - 1\right) Q_c\right] / Q_h\left(1 - \frac{T_0}{T_h}\right)$$

$$\eta_{ex2} = \left[\left(\frac{T_0}{T_c} - 1\right) Q_c + W_e\right] / Q_h\left(1 - \frac{T_0}{T_h}\right)$$

4. SIMULATION RESULTS AND DISCUSSION

In our simulation, the working medium is helium and the working pressure is 6.0 MPa. The heating and ambient temperatures were 650 °C and 20 °C respectively. Fig2 demonstrates the cooling capacity and the electrical power of the HDTAR as functions of the resistance and capacitance of linear alternator. In Fig.2, only the concerned area was presented. A maximum cooling capacity of 340 W was obtained as well as an electrical power of 213 W for one unit with 22 Ω resistance and 10 μF capacitance. Meanwhile, a maximum electrical power of 284 W can be generated with 292 W cooling capacity for one unit when the resistance and capacitance were 67 Ω and 10 μF, respectively. According to Fig.2, by changing the resistance and capacitance of the linear alternator, different output proportion between cooling capacity and electrical power can be obtained.

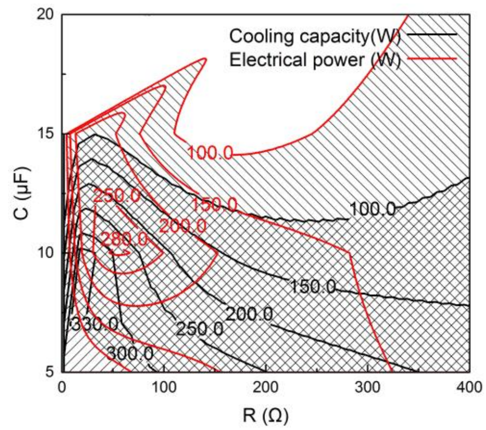

Fig 2 Cooling capacity and electrical power of the HDTAR as functions of the resistance and capacitance of the linear alternator

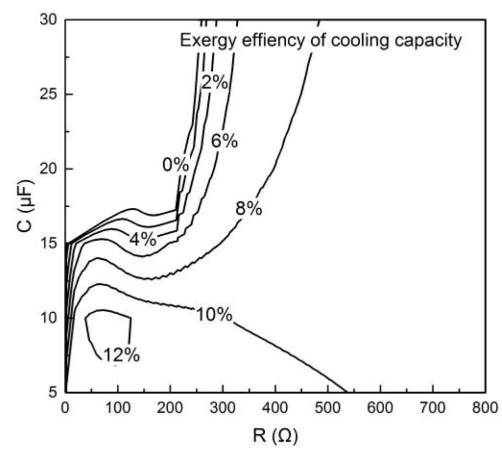

Fig 3 Exergy efficiency of the HDTAR without electrical power as function of the resistance and capacitance of the linear alternator

Fig 3 and 4 demonstrate the exergy efficiency of the HDTAR without and with the electrical power as functions of the resistance and capacitance of the linear alternator. Due to the electric power converted from the expansion work of the TAR, exergy efficiency of the HDTAR combined cooling and power is greatly improved. The maximum exergy efficiency increases from 12.7%

without the electricity power to 21% with the electricity, when the resistance and capacitance were 98 Ω and 10μF respectively. At the same time, 212.6 W cooling capacity at 110 K and 251.5 W electrical power could be obtained for one unit of the HDTAR.

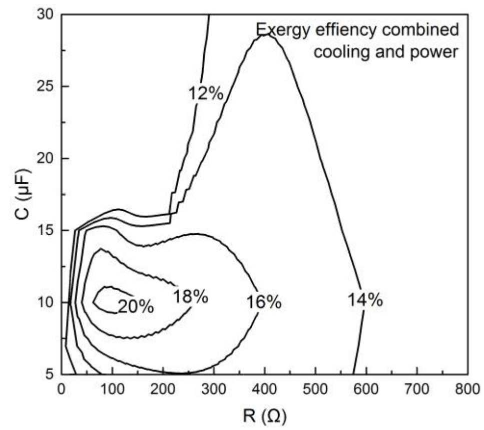

Fig 4 Exergy efficiency of the HDTAR combined cooling and power as functions of the resistance and capacitance of the linear alternator

5. CONCLUSIONS

In this paper, a new type of HDTAR is proposed. Based on the conventional HDTAR, linear alternators are adapted to replace the traditional phase adjuster of the TAR. The linear alternator can not only provide a suitable impedance condition for the TAR to achieve a good operation, but also recover the expansion work at the outlet of the TAR to electric power. According to the simulation results, more than 1 kW cooling power can be obtained for whole system with about 650 W electrical power. In addition, the maximum exergy efficiency without electricity of 12.7% and that of 21% with electricity were achieved respectively. It is believed that this new kind of HDTAR will have a good application prospect in the distributed natural gas liquefaction area.

ACKNOWLEDGEMENT

This work is supported the National Key Research and Development Program of China (No. 2016YFB0901403) and Beijing Natural Science Foundation (3181002).

REFERENCE

[1] Shell LNG outlook 2018. Available at: https://www.shell.com/energy-and innovation/natural-gas/liquefied-natural-gas-lng/lng-outlook.html.

[2] Mokhatab S., Mak J.Y., Valappil J.V., et al. Handbook of liquefied natural gas. Gulf Professional Publishing, 2013.

[3] Radebaugh R., McDermott K.M., Swift G.W. and Martin R.A., Development of a thermoacoustically driven orifice pulse tube refrigerator. In Proceedings of the Interagency Meeting on Cryocoolers, 1991, Plymouth, MA, page 205-220.

[4] Luo E.C., Dai W., Zhang Y., et al. Thermoacoustically driven refrigerator with double thermoacoustic-Stirling cycles. Applied Physics Letters, 2006, 88(7): 074102.

[5] Dai W., Luo E.C., Hu J.Y., et al. A heat-driven thermoacoustic cooler capable of reaching liquid nitrogen temperature. Applied Physics Letters, 2005, 86(22).

[6] Hu J.Y., Luo E.C., Dai W., et al. A heat-driven thermoacoustic cryocooler capable of reaching below liquid hydrogen temperature. Chinese Science Bulletin, 2007, 52(4): 574-576.

[7] Swift G.W., Wollan J.J., Thermoacoustics for liquefaction of natural gas. Gas TIPS, 2002, 8(4): 21-26.

[8] Arman B., Wollan J.J., Kotsubo V., Backhaus S., Swift G.W., 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.

[9] http://www.chartindustries.com/Industry/Industry-Products/Gas-Systems/Qdrive/Qdrive-Products/Cryocoolers/Cryocoolers-2S102K

[10] http://www.aster-thermoacoustics.com.

[11] Zhang L.M., Hu J.Y., Wu Z.H., Luo E.C., Xu J.Y., Bi T. J., A 1 kW-class multi-stage heat-driven thermoacoustic cryocooler system operating at liquefied natural gas temperature range. Applied Physics Letters, 2015.

[12] Backhaus S, Tward E, Petach M. Travelling-wave thermoacoustic electrical generator. Appl Phys Lett 2004;85:1085–7.

[13] Wu ZH, Zhang LM, Dai W, et al. Investigation on a 1 kW traveling-wave thermoacoustic electrical generator. Appl Energy 2014;124:140–7.

[14] Wu ZH, Yu GY, Zhang LM, et al. Development of a 3 kW double-acting thermoacoustic Stirling electric generator. Appl Energy 2014;136:866–72.

[15] Bi TJ, Wu ZH, et al. Development of a 5 kW traveling-wave thermoacoustic electric generator. Appl Energy 2017;185:1355–61.

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

