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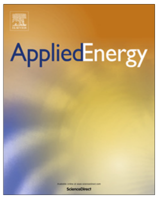

# An efficient pulse tube cryocooler for boil-off gas reliquefaction in liquid natural gas tanks ☆

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## HIGHLIGHTS

- A reliable and compact cryocooler has been developed for BOG reliquefaction.
- The cryocooler offers 1.2 kW of cooling power at a 120 K cooling temperature.
- The overall relative Carnot efficiency exceeded 20%.

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## ABSTRACT

Small liquid natural gas (LNG) distribution stations require compact, highly efficient cryocoolers to reliquefy boil-off gas in the LNG tank. This paper describes a pulse tube cryocooler measuring 420 mm × 690 mm × 780 mm and weighing 180 kg. With low input electric power, the relative Carnot efficiency exceeded 20%. Increasing the power to 10 kW, the cryocooler produced approximately 1.2 kW of cooling at 120 K. Approximately 295 normal cubic meters of boil-off natural gas per day can be condensed. If heat transfer in the main heat exchanger is improved, cooling power and efficiency could be further improved. This development offers an efficient, compact, and reliable configuration for energy saving in LNG distribution stations.

## 1. Introduction

Natural gas (NG) is a viable renewable energy option for bridging our energy gap into the next century. It is recognized as a safe and environmentally responsible fuel and its use has resulted in reduced emissions in many parts of the world. NG has been the fastest growing energy resource throughout the world for more than two decades. Many NG distribution stations will be built in the next few years [1]. Because of the substantial volume reduction, the liquefied form of NG is the preferred manner for these stations to store and transport the gas. Liquid NG (LNG) is stored in special tanks with well-insulated walls. Because of unavoidable heat transfer from the surroundings, LNG is vaporized, which generates boil-off gas (BOG).

In large-scale terminals, BOG is either recondensed using a portion of the cold LNG sendout, used as a fuel source to power prime movers, or reliquefied using refrigerators [2–6]. No BOG venting is permitted during normal operation. In small-scale distribution stations, measuring a few hundred cubic meters, the quantity of BOG is substantially lower and the first and second methods are not applicable. Conventional liquefaction processes based on the Joule–Thomson and Brayton cycles are too large to be compatible with small distribution stations [7]. Thus, novel cryocoolers with cooling capacities of a few kilowatts at 120 K are urgently desired for use in these stations.

The Stirling-type pulse tube cryocooler is a compact, long-lifetime cryocooler with high efficiency [8]. It consists of two parts: a linear compressor and a cold finger. In the linear compressor, electric power is converted into acoustic power. In the cold finger, the acoustic power is used for refrigeration. Initially, the pulse tube cryocooler was developed to cool infrared detectors for aerospace

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**Nomenclature**

| | | | |
|---|---|---|---|
| $A_{piston}$ | piston area | $I$ | current |
| $p$ | pressure | $Q_0$ | rejected heat |
| $Q_c$ | cooling power | $Re$ | real part of impedance |
| $R_{mech}$ | mechanical resistance | $T_0$ | room temperature |
| $T_c$ | cooling temperature | $v$ | velocity |
| $W_{piston}$ | acoustic power delivered by piston | $\eta$ | overall relative Carnot efficiency |
| $\eta_{cf}$ | relative Carnot efficiency of cold finger | $\eta_{com}$ | compressor efficiency |
| $\tau$ | transduction coefficient | $\vert\ \vert$ | magnitude of complex number |
| $\sim$ | complex conjugation | | |

and military applications. Its cooling capacity is often less than 10 W. Recently, the cooling capacity of the pulse tube cryocooler has been increased to more than 100 W for cooling high temperature superconducting equipment [9–12]. In 2005, Arman et al. built a system including three pulse tube cryocoolers driven by a thermoacoustic heat engine for liquefaction of NG [13]. The three cryocoolers are designed to work at different temperatures to successively cool down the NG. This system produced an efficiency of 45% liquefaction and 55% combustion of an incoming gas stream [13]. Unfortunately, no more progress was reported. Generally, one single-stage pulse tube cryocooler can only work at one cooling temperature. If the natural gas is cooled from room temperature to liquefaction temperature, it is not energy-efficient to use one pulse tube cryocooler to cooling the gas because of the great temperature difference between the gas and the cold heat exchanger. Meanwhile, it is very suitable to use it to cool the boil-off gas whose temperature is almost the same as the liquid gas. So this paper introduces a pulse tube cryocooler to reliquefy BOG in small LNG distribution stations for energy savings.

## 2. Theoretical design

A schematic of the pulse tube cryocooler is shown in Fig. 1(a). The system is filled with high-pressure helium. The helium is driven back and forth by pistons. In the regenerator, when the gas parcels (as shown in Fig. 1(b)) are on the side of the cold heat exchanger, they expand and absorb heat from the regenerator; when the gas parcels are on the side of the main heat exchanger, they are compressed and reject heat to the regenerator. Thus, the gas parcels along the regenerator work together like a bucket-brigade to pump heat from the cold heat exchanger to the main heat exchanger. As long as the cold heat exchanger is cold enough, the NG is liquefied around it.

The optimum length of the regenerator to obtain maximum efficiency is mainly determined by the working frequency. At certain frequencies, efficiency does not change with increasing cooling power, but it does change to some extent with the filling of the screens. Based on a previously developed numerical model [14,15], Fig. 2 shows the influence of the regenerator length on the relative Carnot efficiency, $\eta_{cf}$ (cooling power/acoustic power/Carnot efficiency), of the cold finger. To eliminate the influence of the pulse tube in the simulation (the pulse tube also has influence on the performance as shown in Fig. 4 and it is difficult to choose an appropriate size for it to match with the regenerator when optimizing the regenerator), only the main heat exchanger, regenerator, and cold heat exchanger were simulated. The cooling temperature, regenerator diameter, working frequency, and charging pressure were set as 120 K, 120 mm, 50 Hz, and 3 MPa, respectively. The volume flow rate at the inlet of the main water cooler was kept constant. The volume flow rate at the outlet of the cold heat exchanger was optimized to ensure maximum efficiency. It can be seen that there was an optimum length for each regenerator. With lower mesh screens, the optimum length was longer. With 300 mesh screens, the cryocooler achieved the highest efficiency.

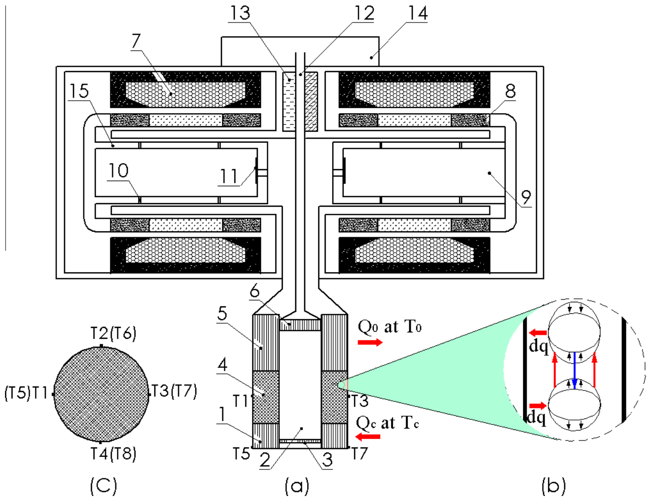

**Fig. 1.** (a) Schematic of the pulse tube cryocooler, where 1 is the cold heat exchanger, 2 is the pulse tube, 3 is the flow straightener, 4 is the regenerator, 5 is the main heat exchanger, 6 is the secondary heat exchanger, 7 is the motor stator, 8 is the moving magnet, 9 is the reservoir in the piston, 10 is the orifice, 11 is the check valve, 12 is the inertance tube, 13 is the cooling water, 14 is the reservoir connected with the inertance tube, and 15 is the piston. (b) The working process of the gas parcels in the regenerator. (c) Distribution of the thermometers around the cold heat exchanger and regenerator.

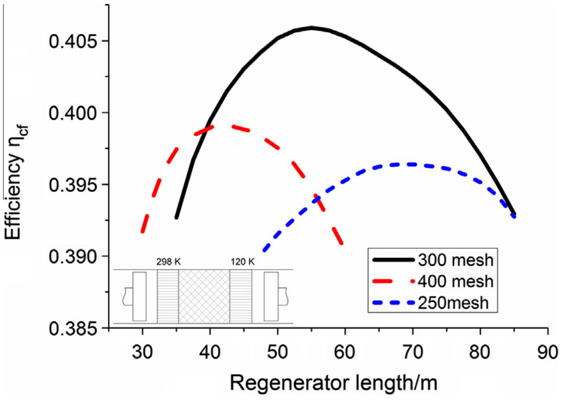

**Fig. 2.** Influence of the regenerator length on efficiency.

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