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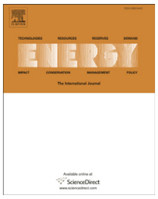

An efficient looped multiple-stage thermoacoustically-driven cryocooler for liquefaction and recondensation of natural gas

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ABSTRACT

With increasing demand for liquefied natural gas, high-efficiency and compact facilities are vital for dealing with natural gas liquefaction or boiled-gas recondensation. This study introduces a looped multiple-stage thermoacoustically-driven cryocooler system that operates in the temperature range of natural gas liquefaction and which has good prospects for meeting such demand. Because of the looped configuration, the system has the potential to achieve efficient traveling-wave thermoacoustic conversion and acoustic power transmission. The basic operating principles are described. A thorough numerical simulation is performed on the influence of the flow-area ratio of the regenerator to that of the resonance tube, which is found to be critical to system performance. To better understand the mechanism, acoustic impedances of the heat engine regenerator and the exergy losses are presented. The dependence of the load impedance on the flow-area ratio is also discussed. An experimental setup was built to verify the numerical simulation. The experimental results show good consistency with those of the simulation. The experimental system achieved a maximum total cooling capacity of 880 W and exergy efficiency of 7.8% at 110 K, corresponding to 65% liquefied natural gas production-efficiency for incoming gas at 300 K or about 74% recondensation efficiency for boiled gas.

1. Introduction

NG (Natural gas), the cleanest fossil fuel, has remained the fastest growing energy resource in most regions of the world for more than two decades [1]. LNG (Liquefied natural gas), being a denser fluid, is convenient for transport and storage. LNG facilities are classified into several types, depending on their demands and functions. Small-scale facilities are used to distribute LNG to inaccessible customers using gas pipelines for supplying refuse trucks, public transport, and in recondensation of the boiled-off gas [2–4]. However, conventional liquefaction systems inevitably require mechanical compressors and electrical power stations, which lead to low reliability and poor efficiency [5]. Thermoacoustic technology—a new energy-conversion technology—is probably one of the best candidates to meet the demand for small-scale facilities. Two representative applications, the THE (thermoacoustic heat engine) and PTC (pulse-tube cooler), have shown great promise because of their mechanical simplicity and high reliability. The acoustic power spontaneously generated by a THE can be used to drive a PTC to obtain cooling power, giving rise to a so-called thermoacoustically-driven PTC system. In 1990, the first thermoacoustically-driven PTC system capable of reaching a temperature of 90 K was introduced by Radebaugh et al. [6], offering an inspiring prospect because it had no moving parts and was structurally simple. This successful preliminary development immediately stimulated industry-wide interest. In 1998, first-stage development of a thermoacoustically-driven PTC system, known as the LNG prototype facility, provided 2000 W of cooling power at a temperature of 130 K, corresponding to 140 gal/day of LNG liquefaction [7]. The second stage of development achieved 350 gal/day of LNG liquefaction [8]; however, because of the complexity of the system, further research has not yet been reported. Since then, most researchers have transferred their attention to obtaining lower no-load temperatures and focusing on coupling mechanisms [9–14]. Conventional thermoacoustically-driven systems inevitably have long large-diameter resonance tubes because of the

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standing-wave acoustic field, which leads to non-compact systems and poor efficiency. In 2010, De Blok developed a four-stage looped traveling-wave THE [15]. This system incorporated multiple thermoacoustic engines in a closed traveling-wave loop to achieve acoustic transmission and simultaneously reduce the heat engine regenerator flow loss by increasing its flow area. Because of its compact size and potential high efficiency, this novel multi-stage thermoacoustic engine has been a focus of recent research [16–18]. In 2013, a tentative experimental system using this novel heat engine to drive multiple PTCs was tested for the first time by the authors' group [19], and showed good prospects for NG liquefaction in small-scale plants.

There are several parameters that play significant roles in determining the performance of the system, including the lengths of the regenerator and the resonance tube, porosity of the regenerator, and the load coupling location, which have been widely studied [20–24]. This paper proposes and discusses a new but similar important parameter. Considering that choosing the proper acoustic impedance for a multi-stage looped system is crucial for balancing the exergy loss in the heat engine, resonance tube, and PTC, this paper mainly focuses on the flow-area ratio of two important components: the regenerator and the resonance tube. To date, there has been little theoretical study or experimental verification of this parameter. A theoretical analysis was first carried out to understand the mechanism; experiments were then conducted to verify the theoretical analysis.

2. Numerical simulation and thermodynamic analysis

2.1. Basic operating principle

In principle, a closed traveling-wave loop may include any number of identical thermoacoustic subsystems; three- to six-stage systems are, however, appropriate for practical applications. A three-stage system was selected for this study. The three-stage thermoacoustically-driven PTC system is schematically shown in Fig. 1. Three identical THEs were evenly placed in a closed traveling-wave loop, in which a PTC was connected to the branch of each THE outlet. Each subsystem included a traveling-wave THE and a PTC. As seen in Fig. 2, each THE included two water-cooled ambient HX (heat exchangers), a regenerator, a heater block, a thermal buffer tube, and a resonance tube. The PTCs included an ambient HX, a regenerator, a cold head, a pulse tube, a flow straightener, and a phase shifter (i.e., an inertance tube plus a reservoir).

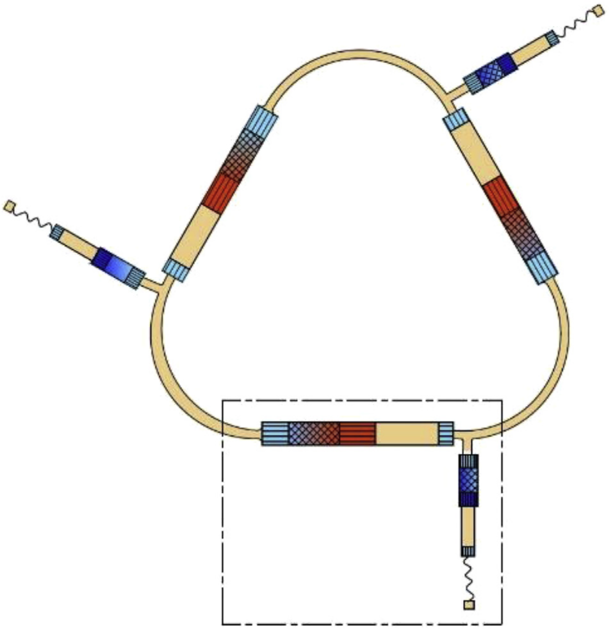

Fig. 1. Schematic view of 3-stage looped thermoacoustically driven cooling system.

The acoustic power generated in the heat engine regenerator is the result of the thermoacoustic effect. This includes all acoustic effects in which heat conduction and entropy variations of the (gaseous) medium play a role [25]. The THE heater block is heated by a high-temperature heating source and the main ambient HX is cooled by water, thereby establishing a temperature gradient across the regenerator. When this axial temperature gradient exceeds a critical value, a self-excited thermoacoustic oscillation is generated and acoustic power is amplified across the temperature gradient. Part of the acoustic power is consumed by the PTC to generate cooling power, while the rest is recycled to the next subunit. Compared with previous thermoacoustically-driven PTC systems, this multi-stage system has the advantages of compact size (small-diameter resonance tube) and high efficiency because of the traveling-wave thermoacoustic conversion and transmission. However, low acoustic impedance in the heat engine may cause large flow losses. Increasing the heat engine regenerator flow area can lower the flow velocity and consequently increase the local acoustic impedance in its regenerator. In addition, significant DC (direct current) flow loss can occur in the closed loop. In our experimental configuration, this problem was avoided by inserting an elastic membrane, made of special elastic and light rubber, in the loop. As seen in Fig. 3, the two parts of the cavity are connected by an elastic membrane attached by two flanges. It can therefore propagate pressure waves but totally block DC flow.

2.2. Numerical simulation

The geometrical parameters for the subsystem are given in Table 1. As mentioned, the flow-area ratio between the heat engine regenerator and the resonance tube plays an important role in achieving efficient thermoacoustic conversion, so the influence of this parameter is one of our theoretical focuses. Because a PTC can be presented as an acoustic load, the load impedance is another crucial parameter for system performance. The purpose of our simulation is to investigate how the flow-area ratio and acoustic load impedance affected the thermodynamic performance and, further, to identify the internal operating mechanism. The simulation was conducted using the *SAGE* program [26], which is a one-dimensional simulation model based on thermal and fluid dynamic equations for engineering models, such as those of a spring–mass-damper resonant system or a Stirling-cycle machine.

In the simulation, the ID (inner diameter) of the THE regenerator was kept at 80 mm. All other dimensions were the same as given in Table 1, except for the diameter of the resonance tube, thereby allowing the flow-area ratio to be changed. Using operating conditions of 7 MPa of helium gas, a heating temperature of 923 K, and ambient temperature of 293 K, the calculation was carried out at the cooling temperature of NG liquefaction, i.e., 110 K. The thermodynamic performance is represented by the cooling power and total exergy efficiency, as defined in Eq. (1):

$$\eta_{ex} = \frac{Q_c\left(\frac{T_0}{T_c} - 1\right)}{Q_h\left(1 - \frac{T_0}{T_h}\right)}, \tag{1}$$

where Q_c is the heat output of the cold head, Q_h is the heat input of the heater block, and T_c, T_0, T_h are the temperatures of the cold