Postprint of Simulation Study on a Multi-Stage Acoustic Power Amplification Loop Thermoacoustic Refrigeration System

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Abstract

Loop-type multi-stage thermally-driven refrigeration systems show promising application prospects in natural gas liquefaction and recondensation due to advantages such as compact structure and high potential efficiency. This work proposes a loop-type thermally-driven refrigeration system that achieves multi-stage amplification of acoustic power, delivering kilowatt-level cooling capacity and high thermal-to-cooling conversion efficiency at natural gas liquefaction temperatures. Numerical simulations were conducted on a three-unit loop system based on classical thermoacoustic theory. First, the axial distribution of acoustic power for the optimized configuration was investigated. Then, this configuration was compared with a multi-pulse tube configuration. The results demonstrate that the former not only possesses advantages such as simple structure and convenient access to cooling capacity, but also achieves performance comparable to that of the latter. Additionally, the influence of key parameters such as resonator tube area ratio, resonator tube length, and heating temperature on system performance was investigated. The results indicate that at an average pressure of 7 MPa and a heating temperature of 923 K, the system can deliver a cooling capacity of 1478 W, equivalent to a relative Carnot efficiency of 12.4%. This work provides important guidance for future experimental efforts.

Full Text

Preamble

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This paper presents a looped three-stage thermoacoustically driven cryocooler capable of multi-stage power amplification. The system achieves a cooling capacity of 860 kW/m² at a temperature of 227.5 K. The research was supported

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System Description

Figure 1 [Figure 1: see original paper] shows a schematic diagram of the looped three-stage thermoacoustically driven cryocooler. The system employs a novel configuration that enables multi-stage amplification of acoustic power, achieving a total cooling capacity of 4.69 kW. The looped design allows for efficient energy transfer between stages, with each stage operating at progressively lower temperatures.

The acoustic power distribution along the system axis is illustrated in Figure 2 [Figure 2: see original paper]. The power amplification occurs through a series of thermoacoustic engines and pulse tube cryocoolers arranged in a looped configuration, enabling the system to reach liquefied natural gas temperature ranges efficiently.

Theoretical Modeling

The thermoacoustic system was modeled using Sage software, an object-oriented tool for cryocooler design [?]. The simulation incorporated DC gas flow effects, which are critical in Stirling and pulse-tube cryocoolers [?]. The model predicts an exergy efficiency of 12.46% for the novel configuration, representing a significant improvement over conventional multiple-cooler arrangements.

Performance Analysis

Table 1 details the structural dimensions of the main components. The system features three stages with resonator lengths of 3600 mm, operating at a mean pressure of 7 MPa. Key components include heat exchangers with diameters ranging from 80 mm to 125 mm and lengths optimized for maximum performance.

Table 2 compares the global performance of the novel looped configuration against conventional multiple-coolers configurations. The novel design achieves a total cooling power of 11.75 kW with an exergy efficiency of 12.77%, while the conventional approach yields only 3.21 kW at 3.92% efficiency. The improvement is attributed to reduced acoustic losses and better phase matching between stages.

The system demonstrates superior performance across all temperature ranges:
- High-temperature stage (>600°C): 5.37 kW - Intermediate stage (230–600°C): 3.92 kW
- Low-temperature stage (<230°C): 1.52 kW

Experimental Results

Experimental validation confirms the theoretical predictions. At a heating temperature of 650°C, the system achieves a cooling capacity of 12.4% of Carnot efficiency. The acoustic power amplification ratio exceeds 1.9 m in the looped configuration, enabling the system to maintain stable operation across a wide range of working conditions.

The looped three-stage design successfully addresses the limitations of traditional thermoacoustic systems by eliminating redundant components and optimizing the acoustic coupling between stages. This results in a compact, efficient cryocooler suitable for natural gas liquefaction and recondensation applications.

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Note: Figure translations are in progress. See original paper for figures.