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A thermoacoustic refrigerator driven by a low temperature-differential, high-efficiency multistage thermoacoustic engine

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HIGHLIGHTS

- Numerical calculation for modeling thermoacoustic (TA) cooler driven by TA engine.
- We determine configuration that enables low-temp. oscillation and high efficiency.
- We derive thermal efficiency when temp. ratio of the prime mover is changed.
- The TA cooler that we configured realizes oscillation at $\Delta T = 110.8$ K.
- The percentage of the Carnot efficiency of the entire apparatus is over 21%.

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ABSTRACT

A multistage thermoacoustic engine could potentially lower the critical onset temperature, which in turn is known to be successfully lowered with multistage amplification. However, not all of the regenerators of a multistage thermoacoustic engine can be set at the peak of the real part of the acoustic impedance distribution and therefore efficiency is generally low. The development of a thermoacoustic engine that has both low temperature oscillation and high efficiency is essential for any practical application. We performed a numerical calculation for a double-loop type thermoacoustic refrigerator driven by a multistage thermoacoustic engine. We determine the configuration that enables a low temperature oscillation and high efficiency. We also obtain the dependency on the temperature ratio of the prime mover for the temperature ratio of the refrigerator, acoustic field, and thermal efficiency. A low temperature drive with high efficiency can be achieved within a multistage thermoacoustic engine.

1. Introduction

A thermoacoustic engine is an external combustion engine based on the Stirling cycle [1]. It has the potential to take work out of multiple heat sources such as a combination of industrial waste heat and solar energy. This type of engine also has the advantage of low cost and low maintenance as it has no moving parts [2,3]. In addition, by forcing the gas inside the regenerator to oscillate, the temperature gradient in the regenerator can be used for refrigeration [4,5]. When a prime mover that generates sound waves from heat is combined with a refrigeration technique that also uses sound waves, a heat-driven refrigerator with no moving parts can be produced [6,7].

However, there is an obstacle to the practical application of this idea. Whilst the temperature of most industrial waste heat ranges from 400 K to 600 K, the critical onset temperature of a thermoacoustic engine is higher, generally ranging from 600 K to 1000 K [8]. To solve this problem, a multistage thermoacoustic engine that can lower the critical onset temperature has been proposed [9]. Biwa [10] realized a critical onset temperature ratio of 1.19 by installing five regenerators in a loop tube combined with a branched tube. When a regenerator is installed in such a position that the real part of the acoustic impedance is at its peak, then the thermoacoustic engine works at its highest thermal efficiency, as both traveling wave phase and minimum cross-sectional mean volume velocity oscillation conditions hold. However, a multistage thermoacoustic engine using multiple regenerators needs all of these to be positioned to yield a peak in the real part of the acoustic impedance distribution. Because this is difficult to achieve, such engines are generally

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Nomenclature

A_C	cross-sectional area (m^2)
C_p	isobaric specific heat ($J\ kg^{-1}\ K^{-1}$)
H	enthalpy flow (W)
j	imaginary number
p	pressure oscillation (Pa)
Q	heat flow (W)
r	radius (m)
T	temperature (K)
U	cross-sectional mean volume velocity oscillation ($m^3\ s^{-1}$)
W	work flow (W)
x	longitudinal coordinate (m)
Greek letters	
γ	ratio of specific heat
η	efficiency
ρ	density ($kg\ m^{-3}$)
σ	Prandtl number
χ_α, χ_ν	thermoacoustic functions [14,16]
ω	angular frequency ($rad\ s^{-1}$)
subscripts	
0	zero point
2	second law efficiency
all	all
C	cold
Carnot	Carnot efficiency
D	dream-pipe
e	prime mover loop
f	refrigerator loop
H	hot
in	in
L	end point
m	mean
out	out
prog	progressive wave
R	room
r	branched tube
stand	standing wave

inefficient [11]. Although success has been reported in lowering critical temperature differences using multiple regenerators, the appropriate positioning of the regenerator and tube radius to produce both low temperature oscillation and high efficiency has yet not been established. The development of such engines is extremely important for any practical use. We have presented a numerical calculation method for thermoacoustic engines in the past. We have also confirmed the accuracy of the calculation [12]. Using this method, calculations have been conducted for a thermoacoustic refrigerator that used air at atmospheric pressure as working gas. However, the second law efficiency (which will be expressed in Eq. (14)) of this refrigerator was only 11.1% [13]. What caused this was that the working gas under these conditions has high viscous loss and highly attenuated energy transport.

From numerical calculations, this paper describes a high efficiency thermoacoustic refrigerator using helium as working gas. To confirm the performance of the proposed apparatus, we calculated the acoustic field of the entire apparatus, as well as its thermal efficiency as a function of the temperature ratio of the prime mover.

2. Calculation model

Our calculation model comprises a double-loop-type thermoacoustic refrigerator driven by a multistage thermoacoustic engine composed of cylindrical pipes with an inner diameter of 100 mm (see Fig. 1). Units that comprise an ambient heat exchanger, a hot heat exchanger, and a thermally insulated regenerator are installed at three different positions within the prime mover loop. The regenerator has many circular channels; the radii are here denoted r_{1-4} (cf. Table 1). These installation positions and r_{1-4} are set to produce both low temperature oscillation and high efficiency. The calculation method is described in Part 3. To assess the performance of the refrigerator, we use thermal efficiency, which can be calculated by dividing the refrigeration output by the total sum of the heat input amount of three engines installed in the prime mover loop. The working gas is helium at 1 MPa. We use T_H to denote the temperature of the hot heat exchangers, T_R the temperature of the ambient heat exchangers, and T_C the temperature of the refrigerator.

3. Calculation method

The method devised by Rott [14,15] based on the first-order differential equation,

$$\frac{d}{dx}\begin{bmatrix} p \\ U \end{bmatrix} = \begin{bmatrix} 0 & \dfrac{-j\omega\rho_m}{A_C(1-\chi_\nu)} \\ -\dfrac{j\omega A_C}{p_m}\left\{1-\dfrac{\gamma-1}{\gamma}(1-\chi_\nu)\right\} & \dfrac{\chi_\alpha-\chi_\nu}{(1-\chi_\nu)(1-\sigma)}\dfrac{1}{T_m}\dfrac{dT_m}{dx} \end{bmatrix}\begin{bmatrix} p \\ U \end{bmatrix} = \boldsymbol{A}\begin{bmatrix} p \\ U \end{bmatrix} \quad (1)$$

is applied in the numerical calculation. Here, p: pressure oscillation, U: cross-sectional mean volume velocity oscillation, j: imaginary number, ω: angular frequency, ρ_m: mean density, A_C: cross-sectional

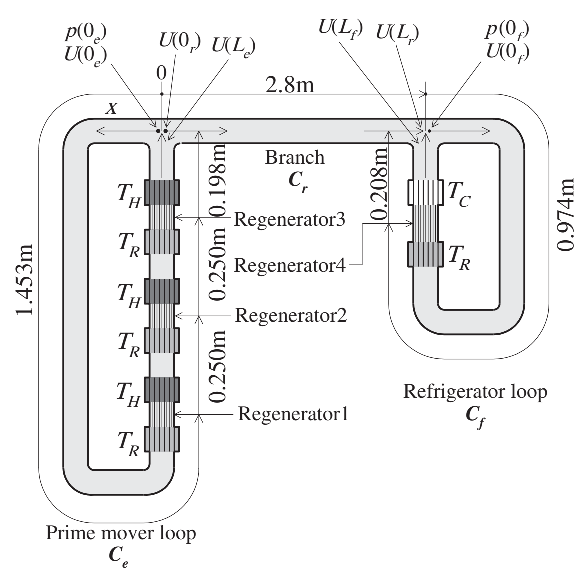

Fig. 1. Analysis model.