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Thermoacoustic travelling-wave cooler driven by a cascade thermoacoustic engine

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HIGHLIGHTS

- Cascade thermoacoustic engine driving a cooler with linear topology is proposed.
- The best features of standing and travelling wave devices are used simultaneously.
- An acoustic absorption element is adopted to adjust the acoustic field.
- Principles and functionality demonstrated through modelling and experimentation.

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ABSTRACT

This paper proposes a novel configuration of a cooler driven by a cascade thermoacoustic engine. It consists of a standing-wave thermoacoustic engine, a travelling-wave thermoacoustic engine and a travelling-wave thermoacoustic cooler in series. The engines provide acoustic energy to drive the cooler. The three main components have a linear topology without the need for using feedback loops. Modelling and simulation of the cascade arrangement, together with the experimental results, are described in this paper. In the presented system, an acoustic absorption element is adopted to induce a higher acoustic power transfer, which increases the travelling-wave component in the acoustic field. It makes the regenerators of both the travelling-wave engine and cooler work in the travelling-wave phase region and allows the thermoacoustic performance offered by both the travelling-wave and the standing-wave to be utilized more effectively.

1. Introduction

Thermoacoustic energy conversion technologies have undergone a substantial development over the recent four decades thanks to the pioneering work of Rott [1–4], Ceperley [5,6] and subsequent demonstration projects undertaken at Los Alamos National Laboratory [7,8]. The thermoacoustic engine (TAE) converts thermal to acoustic energy and this can be used to drive the thermoacoustic cooler (TAC). The system combining the TAE and TAC is called a cooler driven by thermoacoustic engine [9,10]. In such arrangement, when a steep temperature gradient is set up along the regenerator of TAE, the acoustic wave with the oscillating pressure $p_1 = |.p_1|.e^{i(\omega t+\varphi_z)}$ and the oscillating velocity $u_1 = |.u_1|.e^{i\omega t}$ is excited. Here ω is the angular frequency and φ_z is the leading phase of p_1 relative to u_1. When the acoustic wave passes through the regenerator of TAC, a temperature gradient is established along its length corresponding to a certain coefficient of performance (COP). The acoustic wave drives gas parcels in the thermoacoustic regenerators to experience a certain thermodynamic cycle. Then, the conversion from thermal to acoustic energy and the heat pumping occurs without any moving parts in the system. Compared with traditional thermodynamic systems, the cooler driven by thermoacoustic engine has three main advantages: (1) It has a simple structure, no moving parts, low cost of manufacture, and high reliability; (2) By using inert gases as working fluids, this kind of machines is environmentally friendly; (3) The thermoacoustic devices can be driven by low quality energy source such as the exhausting thermal energy and the solar energy, so it is significant for remote rural areas where there may be no access to electricity grid.

In thermoacoustic energy conversion processes, the key mechanism is a heat transfer interaction that takes place between the gas parcels undergoing oscillatory motion and a solid material along which the gas oscillations occur. In thermoacoustic engines, a

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spontaneous acoustic wave is excited which transports heat from the hotter to a cooler place of the solid by a cyclically compressing and expanding gas parcel; in thermoacoustic coolers the acoustically induced compression and expansion of gas parcels leads to heat pumping effects in the solid. However the exact nature of the thermodynamic cycle depends upon the phase difference between the oscillating pressure and the oscillating volume of the gas parcel [11], or in other words (using the equation of state for the gas) between the oscillating pressure p_1 and the oscillating temperature T_1. The relationship between the parameters of the oscillating gas parcel is shown in Fig. 1. The oscillating temperature T_1 is determined by the thermo-relaxation and the oscillating displacement x which is controlled by u_1. Thus, the type of the thermodynamic cycle is influenced by the thermo-relaxation and φ_z.

The early work concerned mainly a variety of standing wave devices [12,13] which were built based on the thermoacoustic theory. In the standing wave devices, gas parcels with $\varphi_z = (2n+1) \times 90°$ realize the conversion between thermal and acoustic energy using a thermodynamically irreversible process defined by an imperfect thermal contact between the working gas and the porous solid material, traditionally referred to as a stack.[1] Although the standing-wave devices are relatively simple to build, their efficiency is limited due to the irreversible thermodynamics on which their thermoacoustic conversion processes rely.

The alternative to the standing-wave devices are travelling-wave devices [5,6,8]. These are usually harder to control in terms of the acoustic wave properties, and traditionally have been more difficult to design and built. However, in such devices, gas parcels with $\varphi_z = 2n \times 90°$ realize a reversible thermodynamic cycle due to a “perfect” thermal contact between the gas parcels and the porous solid material (traditionally referred to as a regenerator). In theory the “perfect” contact would require infinitesimally hydraulic radius of the regenerator, but this would inevitably lead to infinite viscous losses. Therefore in practice a finite hydraulic radius is chosen as a fraction (e.g. typically 0.2) of the thermal penetration depth, which gives acceptable viscous losses but at the same time sufficient thermoacoustic gain and improved efficiency. Subsequently, in practical travelling-wave devices, the oscillating temperature of gas parcels lags their oscillating displacement. Therefore, the phase difference between the oscillating temperature and pressure deviates from $(2n + 1) \times 90°$ because of the thermo-relaxation effects. Under such conditions, in order to improve the thermoacoustic gain and efficiency, the travelling-standing wave phase may be required to match the phase deviation due to the thermo-relaxation.

In practical thermoacoustic systems, there is neither pure travelling-wave mode nor pure standing-wave mode. The thermoacoustic effect is the result of the combined interaction of the travelling-wave component (TWC) and the standing-wave component (SWC) in the thermoacoustic system. The functions of the SWC are energy storage and energy conversion, while the functions of the TWC are energy transfer and energy conversion. In the thermoacoustic engine (TAE), the generated acoustic energy can be transferred by the TWC or stored as the SWC. In the thermoacoustic cooler (TAC), the consumed acoustic energy can be supplied by the TWC or compensated from the stored acoustic energy in the SWC.

Biwa [14] demonstrated thermoacoustic energy conversions which make full use of the TWC and SWC of the acoustic field induced in the resonator. It is claimed that, in order to achieve high gain and efficiency, one has to choose an optimum φ_z which can make both the TWC and SWC contribute to the amplification of the acoustic field intensity. However a new problem arises – namely, if the leading phase φ_z can be chosen in the region of $-180° \le \varphi_z \le 180°$ for the travelling-standing wave, then how to choose the optimum φ_z for the regenerator.

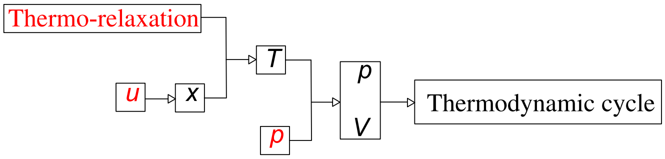

Fig. 1. The relationship between the parameters of the oscillating gas parcel.

Kang et al. [15] investigated the thermoacoustic effect in the travelling-standing wave. The results of their analysis show that to gain a higher acoustic power and efficiency, the hot end of the regenerator in an engine should be close to the pressure anti-node (PAN), and the TWC should propagate from the ambient end to the hot end. To gain a higher cooling power and coefficient of performance, the ambient end of the regenerator in a cooler should be close to the PAN, and the TWC should propagate from the ambient end to the cold end.

Furthermore, Kang et al. [16] analyzed the influence of the parameters of the acoustic field and the regenerator structure on the thermoacoustic conversion and identified the optimum condition for the thermoacoustic conversion. The optimal φ_z depends on the hydraulic radius because φ_z needs to balance the phase deviation generated by thermo-relaxation. Based on the analysis of the thermoacoustic performance in the travelling-standing wave, Kang et al. [17] designed a heat driven thermoacoustic cooler which utilized thermoacoustic effects of both the TWC and SWC. This device has the following advantages: (1) It utilizes simultaneously the thermoacoustic performance contributed by both the TWC and SWC; (2) The acoustic power produced by the engine drives the cooler directly; (3) The feedback tube realizes the recycling process of the residual acoustic power out of the cooler. However, the toroidal topology is more difficult to build than the linear one and also suffers from a circulating second-order mass flow, referred to as Gedeon streaming, which can reduce the efficiency. Gedeon streaming [8] has been successfully suppressed by exploiting the time-averaged pressure gradient developing in an oscillating flow through an asymmetric channel, however this consumes acoustic power. In addition, fabricating asymmetric channels adds complexity that is undesirable in commercial devices.

Thus, this paper proposes a novel configuration of a cooler driven by a cascade thermoacoustic engine, as shown in Fig. 2. It consists of a standing-wave thermoacoustic engine (SWTAE), a travelling-wave thermoacoustic engine (TWTAE) and a travelling-wave thermoacoustic cooler (TWTAC) in series. The two engines are the source of acoustic power to drive the cooler. In the device, an acoustic absorption element (AAE) is used to introduce a higher acoustic power transfer, which increases the TWC in the acoustic field. It makes the regenerators of both the TWTAE and the TWTAC work in the travelling-wave phase region and utilize effectively the thermoacoustic performance contributed by both the TWC and SWC, which improves the overall efficiency of the device.

2. Apparatus

A prototype cooler driven by a cascade thermoacoustic engine has been constructed according to the present concept and the detailed modelling results. Fig. 3 is a photograph of the device. The pressure container elements are built out of 304 grade of stainless-

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[1] In the context of subsequent discussion on the travelling-standing wave concept, and for simplicity this paper will use terminology “regenerator”, for both standing and travelling wave devices considered here.