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Review

Thermoacoustic prime movers and refrigerators: Thermally powered engines without moving components

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A B S T R A C T

Thermoacoustic engines attract much attention for their lack of moving parts and relatively benign environmental impact. In this review, an introduction of the thermoacoustic effect is supported by a summary of related theoretical models for thermoacoustics. An overview of the current research and experimental prototypes including typical thermoacoustic prime movers, thermoacoustic refrigerators, thermoacoustically driven pulse tube refrigerators, thermoacoustic generators and miniature thermoacoustic engines is presented. The worldwide research activities and the related advances in the thermoacoustic engines, mainly in past 30 years, are reviewed in details. Finally, we present a short summary of promotional studies and perspectives in this developing research field.

Contents

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1. Introduction

The term "thermoacoustics", first used by Rott, is referred to as an interdisciplinary science studying the conversion between thermal energy and acoustic energy [1]. Thermal and/or hydrodynamic interaction between solid walls (or materials) and sound field in the oscillating fluid is able to produce the time-averaged work flow and heat flow along (or opposite to) the direction of the sound wave [2,3]. That is, the thermoacoustic effect includes the acoustic power generation driven by heat flow and the pumped heat flow driven by acoustic power, which is the base for the categorization into thermoacoustic prime movers and thermoacoustic refrigerators. Additionally, thermoacoustic machines may also be categorized into standing-wave and travelling-wave systems, according to the features of sound field.

A thermoacoustic engine is mainly composed of pipes and heat exchangers, but all such solid components are fixed in position. It can be designed for a variety of heat energy sources including fuel gas, solar energy, waste heat, etc. Moreover, the working fluids such as helium, argon and nitrogen are friendly to environment. Further, a thermoacoustic prime mover can be designed to drive a TAR (thermoacoustic refrigerator) or a PTR (pulse tube refrigerator), leading to a moving-component-free refrigeration system. Such a system provides the outstanding advantages of simplicity, reliability, stability and longevity due to no moving component from ambient to cryogenic temperatures [4].

Thermoacoustic phenomena were originally observed from daily life earlier than 200 years ago. In 1777, Byron Higgins discovered that acoustic oscillations in a tube might be excited by suitable placement of a hydrogen flame inside [5]. The oscillation was also found by glassblowers. When a hot glass bulb was attached to a cool glass tube, the tube tip might emit sound [2]. The research on thermoacoustics began with these occasional findings.

In 1850, Sondhauss firstly studied the thermoacoustic effect occurring in a glass tube connected to a glass bulb, which was then named as "Sondhauss tube" [6]. In 1859, Rijke observed and qualitatively analyzed the strong acoustic fluctuation, afterward called Rijke oscillation, when he placed a heated screen in an upright tube [7]. Sondhauss tube and Rijke tube are regarded as the ancestors of thermoacoustic machines. Another variant of thermoacoustic system is Taconis oscillation, which can be a severe nuisance in cryogenic apparatus. These oscillations, often of extremely high amplitude, can occur when a gas-filled tube reaches from room temperature to cryogenic temperatures [8]. Taconis' qualitative explanation of the phenomenon was essentially the same as Rayleigh's [9]. Clement and Gaffney carried out systematic observations of the Taconis oscillation [10].

In 1962, Carter and his colleagues effectively improved the Sondhauss tube. "Stack" was placed in the tube, and the thermoacoustic effect was greatly enhanced. They manufactured the first thermoacoustic engine with obvious acoustic work output, producing 27 W of acoustic power from 600 W of heat [2]. It was regarded as the most important advance in modern experimental thermoacoustics, and marked the beginning of the investigation on practical thermoacoustic machine. In 1979, Ceperley from George Mason University pointed out that the phase relation between the pressure and the velocity of oscillating working fluid in the regenerator of Stirling devices was the same as that in a travelling-wave field. Based on this view, he proposed the notion of a travelling-wave thermoacoustic machine [11]. Since the pressure is in phase with the velocity in a travelling wave, the compression and expansion processes of fluid parcels separate from the heating and cooling processes, respectively. In this case, the irreversibility of poor thermal contact (inherently required in a standing-wave thermoacoustic system) is avoided, and a higher thermal efficiency can be obtained. Although a gain of acoustic power was not achieved in his experiment due to the inappropriate acoustic impedance, Ceperley's conception provided new guide to improving the efficiency of thermoacoustic machines [12]. Generally, the term "stack" is widely adopted as the core component (where the thermal-acoustical conversion occurs) in a standing-wave thermoacoustic system, while the term "regenerator" used for that in a travelling-wave thermoacoustic system.

Theoretical thermoacoustics began in 1868, when Kirchhoff calculated acoustic attenuation in a duct due to the oscillatory heat transfer between the confined gas and the isothermal solid duct wall [2]. In 1896, Rayleigh gave the first qualitative explanation of thermoacoustic oscillations: if the phases of working fluid's motion and heat transfer are appropriate, a vibration may be maintained [9]. If the heat is input to the oscillating fluid at the locus of the greatest fluid density, and the heat is removed from the fluid at the locus of the least fluid density, then the heat energy is converted into acoustic energy. A contrary condition may cause attenuation of the sound wave. So far, this Rayleigh principle has been considered as a reasonable qualitative explanation for sustaining the thermoacoustic vibration inside a duct.

Rott from Federal Institute of Technology, Zurich, Switzerland, was the originator of the modern theoretical thermoacoustics. During 1969–1983, he established the theoretical frame of thermoacoustics from the quantitative models of thermoacoustic fluctuations [1,3,13–17], obtaining a set of linear solutions. His study provided an elementary means for quantitatively analyzing the thermoacoustic machines. Since 1990s, much effort by other researchers has also been extended to the nonlinear thermoacoustics, focusing on the nonlinear thermoacoustic phenomena with large oscillation amplitudes. Detailed discussion on theoretical models will be presented in next section.

Thermoacoustics is now of large interest in the academic circles of acoustics, thermodynamics and cryogenics and also in the related industries. In this review, a summary of the related theoretical models for thermoacoustics will be followed by the typical prototype experiments in the past 30 years. Worldwide research activities and advances in this field will be presented in details according to the categorization of thermoacoustic prototypes. Finally, the efforts on promoting the application of this novel technology will be followed by a short summary and perspective to the research on thermoacoustics.