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CFD simulation of a thermoacoustic engine with coiled resonator ☆

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ABSTRACT

Thermoacoustic energy conversion is based on the Stirling cycle. In their most basic forms, thermoacoustic devices are comprised of two heat exchangers, a porous medium, both placed inside a resonator. Work is created through the interaction of strong sound waves with the porous medium that is subject to external heating. This work explores the effect of resonator curvature on the thermoacoustic effect. A CFD analysis of a whole thermoacoustic engine was developed and the influence of a curved resonator on the thermoacoustic effect is discussed. The variation of pressure amplitude and operating frequency serves as metrics in this investigation. It was found that the introduction of curvature affects the pressure amplitude achieved. Severely curved resonators also exhibited a variation in operating frequency.

1. Introduction

The thermodynamic cycle occurring in thermoacoustic heat engines (TAEs) as well as thermoacoustic refrigerators (TARs) is the Stirling cycle, which was developed in 1816 by Robert Stirling [1]. The original mechanical Stirling engine utilized two pistons and a regenerative heat exchanger [2]. Fig. 1 shows such an engine.

Over the course of one cycle, the working gas is compressed, and it then gives off heat to the heat sink, thus maintaining a constant temperature. Afterwards, the gas is heated at constant volume by the regenerator and then is heated further at the heat source. This heat supply occurs while the gas is allowed to expand and driving the power piston, again at constant temperature. After expansion, the gas is displaced to the heat sink, while cooling off at constant volume by depositing heat to the regenerator, which stores heat between cycle segments [2]. The transition to thermoacoustic technology occurred when Ceperley recognized that sound waves could replace the pistons for gas compression and displacement [3].

1.1. Thermoacoustic engines

The simplest thermoacoustic engines (TAEs) operate with a standing acoustic wave in a resonance tube. This wave causes pressure variations as well as gas displacement. In a quarter-wavelength resonator, comprised of a tube with one open end and one closed end, the pressure anti-node of the wave is located at the closed end. The velocity anti-node is located at the open end. When a gas is subject to such a standing wave and it interacts with a solid wall that is subject to a (externally imposed) temperature gradient, pressure disturbances can be amplified to reach strong amplitudes. In practice, this interaction occurs within a porous regenerative unit commonly referred to as the “stack” in standing wave devices. Ceramic monolith structures are often used as stacks because they offer a large surface-to-volume ratio and exhibit desirable hydraulic performance. In order for amplification to occur, this temperature gradient within the porous medium must be larger than the critical temperature gradient. This critical temperature gradient is determined by the temperature changes the gas would undergo if it were under the influence of a sound wave in adiabatic conditions. The expression for this critical temperature gradient $\nabla T_{\mathrm{crit}} = \frac{\omega p_1}{\rho_{\mathrm{m}} c_{\mathrm{p}} u_1}$ was derived by Swift [4]. It depends on the operating frequency ω, the first-order pressure and velocity in the standing wave p_1 and u_1, as well as the mean gas density ρ_{m} and specific heat c_{p}.

In addition to the simple standing wave engine described above is the traveling wave engine. The difference between the standing wave and traveling wave engine lies in the phasing between velocity and pressure. In standing wave engines, the phasing is such that we need to artificially delay the transfer of heat by utilizing a porous structure with large channels [5] such as the ceramic monolith mentioned previously. In the traveling wave engine, the phasing is such that the heating can inherently occur *after* the compression and the cooling can occur *after* the expansion. Here, the flow channels can be designed much smaller [5]. Consequently, the temperature of the gas is almost always the same as the wall temperature, resulting in heat transfer over very small temperature differences. This process produces inherently less entropy, and is thus more efficient than the standing wave engine [6,7]. In summary, thermoacoustic engines create strong pressure oscillations inside a resonator. These oscillations can be used during a reversed Stirling cycle to provide cooling.

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Nomenclature

c	Specific heat
f	Frequency
p	Pressure
T	Temperature
u	Velocity

Greek symbols

Δ	Change
λ	Wavelength
ω	Angular frequency
ρ	Density

Subscripts

1	First-order
crit	Critical
m	Mean, time averaged
p	Constant pressure

1.2. Thermoacoustic refrigeration

If strong sound waves interact with a porous stack their amplitude is attenuated, which withdraws thermal energy from the stack. Thermal energy is pumped from the stack's cold end (of temperature below ambient) to the exhaust end. Refrigerators and chillers driven by TAEs are a reality today; however they are limited to few, specialized uses, for example in gas liquefaction. The National Institute of Standards and Technology (NIST) in collaboration with Radebaugh built a TAR with 5 W of cooling power at 120 K and a low temperature at no load of 90 K [8]. The main benefit is the lack of moving parts (such as seals), thus reducing maintenance costs. It is noteworthy that TARs can achieve these low temperatures in a single stage, whereas VCRs can only achieve approximately 230 K in a single stage [8]. Cryogenic cooling is not the only application for TARs. A practical example of this design was given by Poese with a freezer for ice cream storage. This small scale chiller featured an annular space around the regenerative unit to achieve traveling wave phasing [9].

The main reason, why TARs have not been implemented on a large scale is based on their inherently low coefficient of performance (COP), which is the ratio of input energy over cooling capacity. Note that it is not an efficiency in the classical sense and thus not bounded

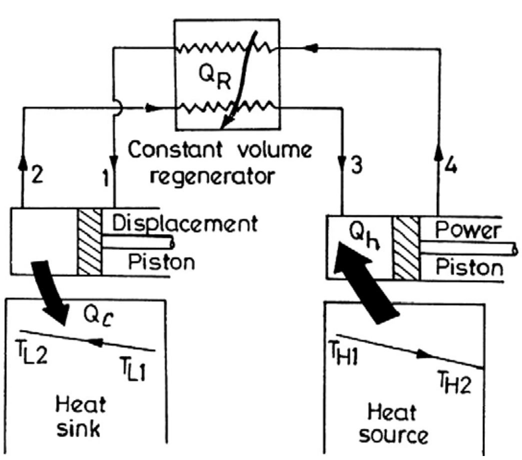

Fig. 1. Schematic of a Stirling engine [2].

by 1. One benchmark of cooling illustrates a spread of COP of traditional refrigeration between 2 and 6, varying with different working fluids and compressor efficiencies [10]. On the other hand, TARs are still operating at COPs of less than one [11]. One reason for this limitation is that the compression of the gas in TARs is more energy intensive than the compression of the liquid working fluid in VC refrigerators. Another limitation of the wide spread implementation is the physical size of thermoacoustic chillers. If the resonator could be coiled as opposed to being designed as a straight tube, the footprint of TAEs and TARs could be reduced and thus be advanced towards broader implementation. The effect of resonator curvature on the performance of TAEs and TARs is not understood. This work provides insights into the effect of curvature in general as well as the severity of curvature on the thermoacoustic effect and operating frequency.

2. Development of the CFD model

In order to investigate different resonator shapes quickly, we developed a computational fluid dynamics (CFD) simulation of a standing wave engine in Fluent. It generally follows the ideas introduced by Nijeholt et al. [12] and Hantschk and Vortmeyer [13].

2.1. Previous numerical simulations in thermoacoustics

Nijeholt used ANSYS CFX to simulate a traveling wave engine inside a Helmholtz resonator, mimicking the design built by Bastyr and Keolian [14]. They used a very coarse grid, and a time step that was just large enough to resolve the expected oscillations. Hantschk and Vortmeyer [13] used Fluent 4.4.4 to simulate a Rijke tube (which is similar to a classic thermoacoustic engine, except that the oscillations are created with one heated wire screen rather than a stack). In their boundary conditions the gas is given a thermal conductivity that is 10 times higher than the realistic value for room temperature. This corresponds to a Prandtl number that is 10 times lower than the real value for their gas at room temperature (which equals approximately 0.7). Entezam et al. [15] also utilized a CFD code to simulate thermoacoustic oscillations in a Rijke tube. In their case applied to a pulse combustor. The most recent previous example of a CFD simulation used to investigate the thermoacoustic effect was provided by Zoontjens [16]. This work considered a single “thermoacoustic couple”, i.e. the interaction of a single stack plate with an oscillating gas, as investigated by Ozoe et al. [17]. Zoontjens' model, was based on previous numerical simulation efforts (without using commercial codes) put forth by Cao et al. [18], Besnoin and co-worker [19,20] and Worlikar and Knio [21], Ishikawa and Mee [22], and Marx and Blanc-Benon [23–26], and finally Piccolo and Pistone [27]. These efforts were used largely to investigate the non-linear behavior of the temperature as a result of the interaction of the oscillations with the stack wall. Our group advanced the numerical simulation by accounting for several thermoacoustic couples through a simulation of a whole TAE.

2.2. CFD simulation of a whole TAE

Our model is based on a mechanically simple standing wave engine with a quarter-wavelength resonator and a porous stack located in the vicinity of the closed end. This standing wave engine was replicated in Gambit. The grid dimensions are 12 mm wide and 150 mm long. The stack of the engine is represented by several walls spaced 500 µm apart. These walls are given a non-zero thickness in order to participate in a heat exchange with the surrounding fluid. The grid is built using triangular cells, with a total cell count of approximately 36,000 cells. Triangular cells were chosen because it allowed to gradually increase the cell density (i.e. the node spacing on the walls by the stack is much smaller than on the closed wall boundary on the left) towards the stack region, where high accuracy in the