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Experimental validation of a looped-tube thermoacoustic engine with a stub for tuning acoustic conditions

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ABSTRACT

Thermoacoustic engines with a looped-tube structure and multiple thermoacoustic stages are able to efficiently utilize low-grade heat. If additional measures to counteract acoustic reflections are taken, similar results can be achieved by using only one single stage. The implementation of a stub, which is a compliant duct closed on one side and T-branched to the engine's loop on the other side, allows a precise tuning of acoustic conditions. By only changing position and length of the stub, phase difference and normalized impedance in the regenerator can be adjusted over a wide range. The method is experimentally validated by this paper. A test-rig is introduced that works with argon at atmospheric pressure. Measurements of thermal and acoustic conditions were conducted for several configurations of the stub. Afterwards, results are used to adjust a numerical DeltaEC-model. The proposed procedure employs simple and reasonable correction parameters. They take minor acoustic losses, nonlinear effects and geometrical errors into account. Eventually, the simulated acoustic field is in very good agreement with experimental results. The stub's acoustic tuning capability is verified. Further, the results show a large mismatch of thermal quantities. Gedeon streaming is expected to be responsible. It is later eliminated by use of a jet pump with a novel design. Hence, a major discrepancy is still observable being related to other effects of thermoacoustic streaming. Eventually, impacts of the jet pump to the acoustic field on system level are analyzed.

1. Introduction

The thermoacoustic effect describes the reversible conversion of heat into the energy of a sound wave. It is based on the thermal interaction of a non-isothermal wall with the oscillating change of displacement and pressure of a gas. Various thermodynamic cycles can be realized. They are applied for heat engines or refrigerators [1].

Thermoacoustic engines come with a simple design without moving parts, utilizing common materials. They can be driven by hazard-free and environmental-friendly gases. These advantages lead to potentially reliable and cost effective setups. Combined with a relatively high efficiency and the ability to work with a small temperature difference, they are an alternative to more developed heat engines, e. g. engines based on the Rankine or Stirling cycle. By this means, they might shift economic hurdles to use low-grade heat and widen the applicable field of waste heat recovery. The general need for energy-efficient technologies is recently pushing developments in the field of thermoacoustics. Advances are substantially supported by the publication of Swift's text book [1] and the simulation software DeltaEC (Design Environment for Low-amplitude Thermoacoustic Energy Conversion) [2].

Starting in 1969, Rott established the theoretical fundament of modern thermoacoustics in a sequence of articles. With the derivation of the so called "Rott's wave equation", an appropriate linear approximation to describe thermoacoustic processes became possible [3]. In 1979, Ceperley realized that the phase difference between motion and pressure oscillation in a Stirling engine is the same as in an acoustic travelling-wave [4]. A new type of thermoacoustic engine with a looped-tube was discovered. Its functionality was first demonstrated by Yazaki et al. in 1998 [5]. However, due to an inappropriate acoustical design, performance was poor. Backhaus and Swift achieved a breakthrough with a variation of this engine type in 1999 [6]. A maximum thermoacoustic efficiency of 30% was accomplished. They reached favorable acoustic conditions by using a quarter-wavelength resonator that simultaneously limited the heat supply to several hundred degrees Celsius [7]. Similar setups exceeded the performance but also relied on a high temperature, e. g. from Tijani and Spoelstra [8]. De Blok [9] proposed a looped-tube engine with a bypass. This improvement allowed the use of low-grade heat with a temperature below 200 °C. The introduction of multiple engine stages evenly distributed along a looped-tube resonator further improved the performance and allowed

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the abandonment of the bypass [10].

This type of multi-stage engine reduces viscous losses in the regenerator by enlarging its cross-sectional area, thereby reducing oscillating gas velocity [11]. Induced acoustic disturbances are "self-matched" by the evenly distributed stages. Preferable acoustic conditions are achieved automatically. The four-stage engine has proven to start operation with a temperature difference of 30 K. An efficiency of 40% relative to Carnot seems to be possible for heat supplied at 150 °C [10]. Jin et al. [12] reported an even lower onset temperature difference of 17 K. Encouraged by these promising results, design principles of multi-stage engines were numerically investigated [13], acoustic field characteristics were examined [14], and optimal positions for load and regenerator were analyzed [15]. The method was also adopted for thermoacoustic engines with two [16] and three stages [17].

Thermoacoustic engines can be driven by various low-grade heat sources. They range from waste heat, either of industrial heritage [18] or from an internal combustion engine [19], and include regenerative heat sources like geothermal or solar [20]. The utilization of cold exergy of liquefied natural gas is also feasible [21]. Generated acoustic power can further be used to drive an acoustic-to-electric converter, e. g. a bi-directional turbine [18] or a linear alternator [22] which can be applied in a "push-pull" mode [23]. Apart from that, the realization of a heat-driven thermoacoustic cooler is possible [14].

In the scope of a numerical study, Kruse et al. [24] showed that a single-stage looped-tube thermoacoustic engine is able to achieve comparable performance as a multi-stage engine. However, it needs an additional acoustic element to match the acoustic field. With the variation of position and length of a stub attached to the looped-tube, they claimed to accurately tune acoustic conditions in the regenerator. A single-stage engine could be advantageous since it has fewer parts, reducing system complexity and investment costs. Furthermore, the stub can be used to modify the acoustic field during operation. This allows an optimal adjustment as a function of either, maximum power or efficiency.

In this paper, the proposed method of tuning acoustic conditions with a stub is experimentally validated. Beginning with an explanation of the concept, the design of the experimental thermoacoustic engine is described. Experimental results are used to verify a numerical model based on DeltaEC. The introduction of reasonable correction parameters is explained. While acoustic conditions are accurately reproducible with the model, major deviations regarding thermal conditions are observed. An attempt to quantify the causes of these differences is taken. Therefore, the implementation of a jet pump with a novel design is described and feedbacks with the acoustic field of the engine are analyzed.

2. Concept of tuning acoustic conditions with a stub

A looped-tube thermoacoustic engine is basically made of two functioning parts: a thermoacoustic core which holds a regenerator sandwiched between two heat exchangers, and a resonator in shape of a feedback loop. The thermoacoustic conversion takes place in the regenerator, amplifying acoustic power. The resonator recirculates acoustic power through the regenerator. An efficient engine must supply different acoustic conditions in both parts to achieve maximum acoustic power $\dot{E}$ at position x [1]:

$$\dot{E}(x) = \frac{1}{2}\,|p_1||U_1|\,\cos(\varphi), \tag{1}$$

with oscillations of pressure p_1 and volumetric velocity U_1, as well as the phase difference φ between both quantities. This becomes clear by examining the length dependent change of acoustic power $\mathrm{d}\dot{E}/\mathrm{d}x$ in a duct [1]:

$$\frac{d\dot{E}}{dx} = -\frac{r_\nu}{2}\,|U_1|^2 - \frac{1}{2r_\kappa}\,|p_1|^2 + Re[g]\frac{|p_1||U_1|\,\cos(\varphi)}{2}. \tag{2}$$

The first two terms on the right hand side contain the specific viscous resistance r_ν and the specific thermal-relaxation conductance $1/r_\kappa$. They describe thermoviscous losses at the contact surface and always consume acoustic power. The third term explains the amplification of acoustic power in a regenerator. It holds the specific gain g which strongly depends on the applied temperature difference.

A regenerator with a small pore size (hydraulic radius is much smaller than the thermal penetration depth) shows a minimum of loss terms, when the impedance $Z = |p_1|/|U_1|$ reaches a value much larger than the characteristic impedance $Z_c = \rho_m{\cdot}a/A$, with mean gas density ρ_m, speed of sound a, and cross-sectional area A. As a result, the normalized impedance Z_n describes the ratio of pressure amplitude $|p_1|$ to velocity amplitude $|u_1|$ normalized by gas properties:

$$Z_n = \frac{Z}{Z_c} = \frac{|p_1|}{|u_1|}\frac{1}{\rho_m a}. \tag{3}$$

Therefore, optimal acoustic conditions in the regenerator exist, when: (I) the phase difference is close to zero, allowing the reversible thermoacoustic-Stirling process, and (II) normalized impedance is raised, mainly to reduce viscous losses in the porous regenerator [11].

On the other hand, a minimum of acoustic transfer losses along the feedback loop is obtained, when acoustic conditions are evenly distributed. Due to their exponential impact to losses in Eq. (2), local peaks of pressure and velocity need to be avoided. This is accomplished by having travelling-wave conditions with a phase difference close to zero and normalized impedance close to one.

The counteracting goals of high normalized impedance in the regenerator and low impedance in the feedback tube can be reached by simply raising the cross-sectional area of the regenerator [11]. However, the local enlargement of gas volume and the high acoustic resistance of the regenerator lead to severe acoustic reflections and disturbances in the resonator. They prevent optimal acoustic conditions, thus, an efficient operation of the thermoacoustic engine. The compliant impedance of the regenerator (including heat exchangers and adjacent cavities for geometric transition) needs to be acoustically matched.

Several attempts have been undertaken to balance acoustic reflections by use of additional acoustic elements. Those can be divided into elements with a large acoustic inertance $L = \rho_m \Delta x/A$ ("narrowed duct" with mean gas density ρ_m, length Δx, and cross-sectional area A) or a large acoustic compliance $C = V/\gamma p_m$ ("widened duct" with Volume V, isentropic exponent γ, and mean pressure p_m). Accurately positioned in respect to the regenerator, their impedance $Z = i\omega L + 1/i\omega C$ induces either a change of pressure amplitude or of volumetric velocity, respectively. In addition, phase difference is influenced [1]. A stub, which is a compliant element, was used by Yu et al. [25] to match a load to the acoustic network of the engine. Acoustic disturbances due to reflections at the load were reduced. Furthermore, they showed that a length variation of the stub influenced the acoustic field. It was used to tune phase and impedance. The effect of stub position was not investigated. Kang et al. [16] applied a stub in combination with a ball valve to their engine with two separate stages. They noticed an impact of the stub length on acoustic conditions and used the ball valve to correct the acoustic field. Jin et al. [26] analyzed phase and impedance adjustment with the implementation of what they called a "compliance tube" and compared it the effect of a "resistance tube". The first is a widened section and can be located either a quarter or a three quarter wavelength away from the regenerator. The latter is a narrowed section placed half of the wavelength behind the regenerator. They explained the acoustical functionality of each element by setting either a soft or a hard boundary to the acoustic field. These boundaries can be used to influence acoustic conditions in the regenerator. A variation of an element with compliant behavior was proposed by Al-Kayiem and Yu [27]. They were able to affect acoustic conditions by changing the volume of a side-branched Helmholtz resonator.