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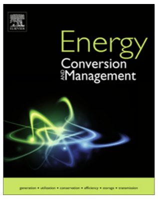

A numerical study of a looped-tube thermoacoustic engine with a single-stage for utilization of low-grade heat

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ABSTRACT

Multi-stage thermoacoustic engines with a looped structure have become a promising technology to use heat at a low temperature level. This study forwards a single-stage engine with comparable capabilities. A stub is used to suppress acoustic impedance disturbances. This conception shows to be a powerful tool to accurately tune acoustic conditions in the regenerator. Furthermore, a systematic parametric study is carried out numerically with DeltaEC to examine their relations. This could help in a system-wide optimization according to various application requirements. The study comprises geometrical parameters of regenerator, heat exchangers, and feedback loop as well as process parameters like operational temperatures, mean pressure and working gas. Discrepancies between ideal conditions on component level and on system level have been observed and an approach to interpret them is given. Recommendations for parameter settings depending on an efficiency or power driven operation are supplied. Since a proper coupling between acoustic load and acoustic field in the loop is essential for a sufficient overall-performance, joining mechanisms have been examined in terms of acoustic impedance and position of the load. Eventually it is shown that the proposed engine type is able to power an acoustic load with a relative Carnot efficiency greater than 50% when heat is supplied at 150 °C and rejected at 15 °C.

1. Introduction

Thermoacoustic devices seem to be a promising technology for utilization of waste heat and are suspect of a steady growing interest especially in the field of research. The thermoacoustic effect induces conversion between thermal and acoustic energy and vice versa. It is applicable for the design of thermoacoustic engines and heat pumps [1]. Many advantages, e.g. simple construction with comparatively low requirements of fabrication, lack of moving parts in thermally stressed components, usage of environmental friendly gases, and the ability for application of low-grade heat are some reasons for the fast development of this sector. However, the technology is only at the primitive phase of commercialisation.

Ceperley [2] was the first to recognize similarities between gas motion and pressure cycles in an acoustic travelling wave and in a Stirling engine with mechanical pistons. A gain of power occurs, if such cycles are executed inside a differentially heated regenerator. Both processes are based on the thermodynamically reversible Stirling cycle. Ceperley also realized that high viscous losses within the regenerator could be decreased by local enlargement of acoustic impedance [3]. Nevertheless, the first successful demonstration of a travelling-wave engine was performed by Yazaki et al. [4] in 1998. They only achieved a relatively poor efficiency presumably due to large viscous energy losses and an imperfect thermal contact in the regenerator. Backhaus and Swift [5] proposed an engine in a torus configuration with a long standing-wave resonator. By adjusting the acoustic network, they reached travelling-wave phasing and high impedance in the regenerator. Encouraged by this breakthrough, Tijani and Spoelstra [6] as well as Haberbusch [7] further improved this configuration and were able to achieve an efficiency relative Carnot of up to 52%. However, this torus-type engine is not suitable for low-grade heat recovery since it requires a temperature difference of several hundred Kelvin to start operation and reaches reported peak efficiency only at heat input temperature of around 600–725 °C. Large viscous losses in the essential standing-wave resonator are responsible for this temperature restriction. Nonetheless, to be economically viable and competitive with conventional systems, thermoacoustic devices

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must see a decrease of operating temperature to a range of 70–200 °C while preserving relative Carnot efficiency [8,9].

Recently, a new type of thermoacoustic devices emerged. Based on Ceperley's suggestion [3] to increase local impedance in the regenerator by enlarging its cross sectional area, de Blok [8] firstly applied this idea in an engine with a bypass geometry and a travelling wave feedback loop. He achieved a minimum onset temperature difference of 85 K and thus significantly reduced minimum operation temperatures. He also showed that usage of multiple thermoacoustic cores evenly distributed along the feedback loop will further reduce the onset temperature difference and would lead to an engine efficiency relative Carnot of at least 40% for heat sources at 150 °C [10,11]. After these promising results, the method was widely adopted for multi-stage engines [12–19]. Jin et al. [20] reported an onset temperature difference of only 17 K for a 4-stage system. Most recently, Wang and Qiu [21] executed a numerical analysis on a 4-stage generator. Those thermoacoustic engines can be driven by low-grade heat sources such as industrial, solar, or geothermal heat.

Zhang et al. [9,22] pointed out that the stage number in an engine has to be optimized after considering a trade-off between operational temperature difference and system performance. An engine with fewer stages might require higher temperature for onset but outperforms an engine with more stages at a higher temperature difference. A smaller number of stages could be beneficial in terms of reducing systems complexity and could furthermore decrease investment costs for commercialisation. On these grounds, the present article describes the layout of a looped tube engine with only one stage. A detailed parametric study is carried out numerically with the software DeltaEC [23] in order to systematically investigate performance and highlight design issues. The analysed parameters are related to acoustic conditions in the regenerator, regenerator design, heat exchanger design, area ratio, and coupling of an acoustic load. Furthermore, the impacts of operating temperatures, mean pressure and gas type are investigated.

2. Basic design and DeltaEC-model

A looped tube single-stage thermoacoustic engine is schematically depicted in Fig. 1. The system consists of several major elements. The thermoacoustic core is the essence of the engine. It builds up from an ambient heat exchanger (AHX), a hot heat exchanger (HHX), and a regenerator (REG) sandwiched in between. The HHX acts as a heat source, the AHX accordingly as a heat sink. Together they induce a temperature gradient along the REG. The feedback tube (FBT) closes the looped waveguide. Since the cross-sectional area of the core is enlarged, an additional cavity is inserted on both sides of the core to allow a geometrical transition. There are two T-joints with side-branches along the FBT. One represents an acoustic load to extract acoustic power out of the engine and the other one is a stub for matching acoustic impedance and suppressing acoustic impedance disturbances in the loop caused by the core and the load.

The parameters for the basic design of the simulation model were chosen to be easily applicable for a real-world device. They are listed in Table 1. Both heat exchangers (HXs) are modelled as two identical parallel plate HXs. Their geometrical layout is inspired by common car radiators with an assumed hydraulic radius of 0.6 mm, a porosity of 70%, and a fin length of 15 mm. REG is simulated as a 20 mm long stack of stainless steel screens with a hydraulic radius of 54.8 μm and a porosity of 80%. The core cavities have a length of 25 mm each. Hence, the thermoacoustic core section spans over 100 mm and leads, combined with the FBT, to an overall engine length of 4 m. The core elements have a diameter of 400 mm and the ratio between core and feedback cross-sectional area is 10.

The load is characterized by complex acoustic impedance. In the basic model, it has a real part of 2.7 MPa s/m^3 and no imaginary component. Together with the impedance of FBT, it determines the fraction of acoustic power which leaves the system and can be supplied to an exterior load.

The stub is a closed side-branch pipe and is used to tune acoustic conditions in REG. By changing its length (thus volume) and position along the loop, it can adjust the impedance ratio and phase difference in a wide range. The stub position of 0.868 m and the stub length of 0.656 m (corresponding to a volume of 0.00824 m^3) will meet the targeted values for normalized impedance, Z_n, and phase difference between pressure and volumetric velocity amplitude, φ, which are 8 and −20° respectively. Further below, the functionality will be explained in more detail.

Heat is supplied at a temperature of 150 °C and rejected to the ambience at 15 °C. The values were chosen to be comparable to experimental data, e.g. from de Blok [10,11]. Please note that these

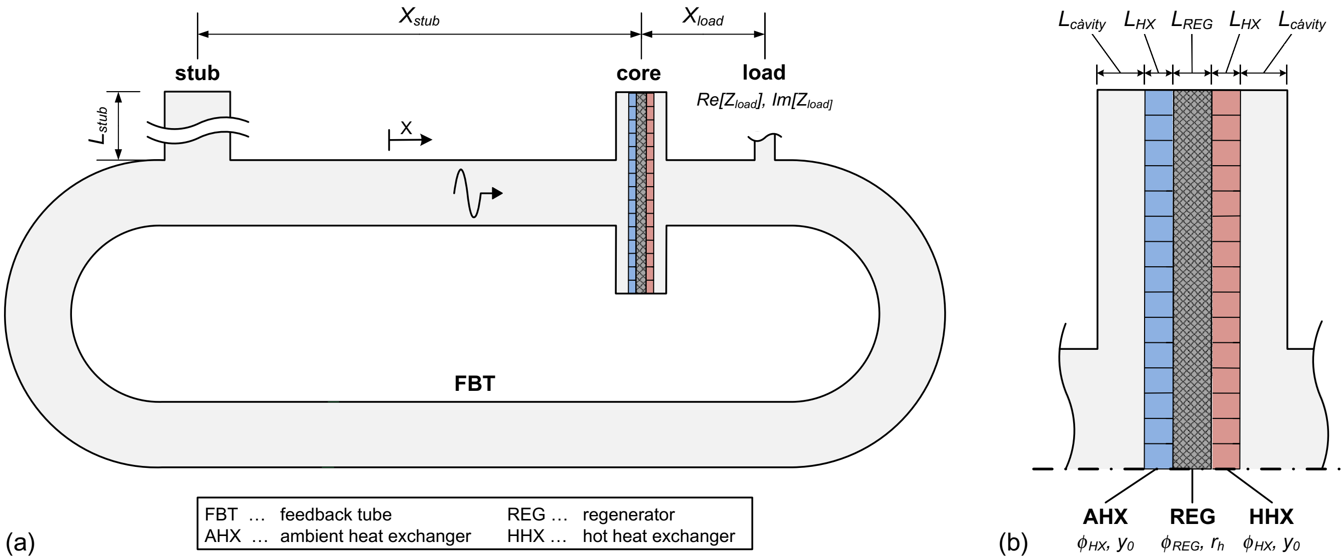

Fig. 1. Scheme of the analysed looped-tube thermoacoustic engine with labels for components and examined parameters; (a) complete engine model, (b) detailed view on the thermoacoustic core section. See Table 1 for explanation of symbols.