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Numerical investigation of a looped-tube travelling-wave thermoacoustic engine with a bypass pipe

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ABSTRACT

A new configuration ("a looped-tube with a bypass pipe") was recently proposed for low temperature travelling wave thermoacoustic engines and a prototype using atmospheric air as the working gas achieved an onset temperature difference as low as 65 °C. However, no further research has been reported about this new configuration to reveal its advantages and disadvantages. This paper aims to analyse this type of engine through a comprehensive numerical research. An engine of this type having dimensions similar to the reported prototype was firstly modelled. The calculated results were then qualitatively compared with the reported experimental data, showing a good agreement. The working principle of the engine was demonstrated and analysed. The research results show that an engine with such a bypass configuration essentially operates on the same thermodynamic principle as other travelling wave thermoacoustic engines, differing only in the design of the acoustic resonator. Both extremely short regenerators and a near-travelling wave resonator minimise the engine's acoustic losses, and thus significantly reduce its onset temperature difference. However, such short regenerators likely cause severe heat conduction losses, especially if the engine is applied to heat sources with higher temperatures. Furthermore, the acoustic power flowing back to the engine core is relatively low, while a large stream of acoustic power has to propagate within its resonator to maintain an acoustic resonance, potentially leading to low power density. The model was then applied to design an engine with a much longer regenerator and higher mean pressure to increase its power density. A thermoacoustic cooler was also added to the engine to utilise its acoustic power, allowing the evaluation of thermal efficiency. The pros and cons of the engine configuration are then discussed.

1. Introduction

Thermoacoustic systems can either generate acoustic work (i.e., p-v work) from thermal energy, or consume acoustic work to transfer heat from low to high temperature [1]. They are the so-called thermoacoustic prime movers or heat pumps, respectively. Essentially, they are acoustical equivalents of Stirling engines or coolers. In 1979, Ceperley [2,3] revealed that, when a travelling sound wave propagates through a regenerator with a positive temperature gradient along the direction of sound wave propagation, the gas parcel experiences a Stirling-like thermodynamic cycle. As such, thermal energy can be converted to acoustic power. Based on this concept, Yazaki et al. [4] demonstrated the first travelling wave thermoacoustic engine which has a thermoacoustic engine core (i.e., a regenerator sandwiched by a pair of cold and hot heat exchangers) in a one-wavelength looped-tube resonator. Backhaus and Swift [5] later developed a travelling wave thermoacoustic Stirling engine which placed the engine core within a torus with a length much shorter than one acoustic wavelength at the operating frequency. A quarter-wavelength standing wave resonator was connected to the torus to provide acoustic resonance. This engine achieved a thermal efficiency of 30%, equivalent to 41% of the theoretical Carnot efficiency. Tijani and Spoelstra [6] later built and tested an engine of this type, and reported that 49% of the Carnot efficiency was achieved.

De Blok made a series of efforts to develop various travelling wave thermoacoustic engines [1,7–9]. He proposed a travelling-wave thermoacoustic engine with coaxial configuration in 1998 [7]. In 2008, he proposed a new configuration (i.e., a looped-tube with a bypass pipe) for a travelling wave thermoacoustic engine, which achieved an onset temperature difference as low as 65 °C [1]. It is denoted as "bypass configuration" hereafter in this paper. Later, he

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also developed multistage looped-tube travelling wave thermoacoustic engines, and applied them to drive a cooler or linear alternator for different applications [8,9].

Similar to Stirling engines [10] and thermo-fluidic oscillators [11], thermoacoustic engines can be externally heated with various heat sources and are capable of utilising low grade thermal energy such as industrial waste heat and solar thermal energy. Owing to their simplicity and absence of moving parts, travelling wave thermoacoustic engines have the potential for developing low-cost power generators and thus have attracted much research effort for developing coolers [12–17] or electric generators [18–34].

In the past decades, great efforts have been made to develop thermoacoustic generators with different configurations and transducers [18–34]. In 2004, Backhaus et al. developed the first travelling wave thermoacoustic electric generator based on a flexure-bearing linear alternator for deep space application. At its most efficient operating point, the system generated 39 W electric power at a thermal-to-electric efficiency of 18% [18,19]. In 2008, Sunpower Inc. developed a coaxial travelling wave thermoacoustic electric generator, which achieved an electric power output of 50 W [20]. Wu et al. constructed a travelling-wave thermoacoustic electric generator that produced 481 W electric power with an efficiency of 15% [21]. Later on, this group developed a solar powered thermoacoustic electric generator which delivered about 200 W electricity [22]. In 2013, based on a flexure-bearing linear alternator, Sun et al. developed a travelling-wave thermoacoustic electric generator using helium at 3.0 MPa as the working gas, which achieved a maximum electric power of 345.3 W with a thermal-to-electric efficiency of 9.3% [23]. In 2014, Wu et al. developed a double-acting thermoacoustic Stirling electric generator which had three thermoacoustic Stirling engine stages and three linear alternators. Using 5 MPa pressurised helium as working gas, the prototype achieved a maximum electric power of about 1.57 kW and a maximum thermal-to-electric conversion efficiency of 16.8% [25]. In 2016, this group increased the power generation of their three-stage travelling wave thermoacoustic electric generator to 4.69 kW [26]. Wang et al. [27,28] also developed and tested two prototypes of thermoacoustic electric generators that were driven by Backhaus and Swift type travelling wave thermoacoustic engines, and achieved promising results.

Along with the development of thermoacoustic generators based on flexure-bearing linear alternators, efforts have also been made to develop inexpensive systems using ultra-compliant linear alternators (e.g., audio loudspeakers) as transducers [29–34]. Yu et al. developed a small-scale inexpensive prototype generator using atmospheric air as the working gas and a six-inch B&C subwoofer as an alternator, and it produced 11.6 W of electrical power [30]. Kang et al. reported a two-stage travelling wave thermoacoustic electric generator using two audio loudspeakers as transducers which generated 204 W electricity. This demonstrated the feasibility of developing inexpensive thermoacoustic electric generators [31].

Despite the different engine configurations for developing these engines, they all work on the same thermodynamic principle, i.e., the Stirling cycle. The difference mainly lies in the different design of the resonator which can be an acoustic resonator, mechanical resonator, or a combination of both. Similar to the flywheel of a Stirling engine, the resonator provides acoustic resonance to enable the gas parcel to complete the thermodynamic cycle within the regenerator. Depending on the characteristics of the acoustic field within the resonator, it can be a standing wave or travelling wave resonator. Backhaus' thermoacoustic Stirling engine used a quarter-wavelength standing wave resonator [5]. Yazaki's engine [4] used a one-wavelength travelling wave resonator. De Blok's' bypass type engine used a travelling wave feedback pipe with a bypass pipe [1]. In his multistage engine, several engine stages share a one-wavelength resonator, leading to better performance [9]. The thermoacoustic generator developed by Backhaus et al. had a mechanical resonator [18,19]. All the other electric generators [21–34] have a combined resonator system.

In general, the design principle of a thermoacoustic engine is to maximise the acoustic power production within the thermoacoustic core, while minimising the loss associated with the acoustic power transmission. A travelling wave resonator is superior to a standing wave one because its acoustic loss is much lower [8,9]. Hence, the development of suitable travelling wave resonators remains a hot research topic. As schematically shown in Fig. 1, the thermoacoustic engine with a bypass configuration developed by de Blok achieved a very low onset temperature difference, which was attributed to the novel design of the resonator [1]. However, the heat power input to the prototype, its net acoustic power production, and its thermal efficiency were not reported in the reference [1]. It is therefore unknown how efficient the prototype was. This is indeed a very interesting and important question. Moreover, there is no further research on this type of engine to analyse its advantages and disadvantages. It also remains unknown if the regenerator length can be increased, without violating the working principle, to utilise heat sources with higher temperatures.

This paper aims to answer these questions through comprehensive numerical research. Firstly, using the DeltaEC programme [35], an engine with this bypass configuration is modelled based on the information of the prototype reported in the reference [1], and the simulations are then qualitatively compared with reported experimental data. The working principle is demonstrated and analysed. The model is then used to design an engine with a much longer regenerator and higher mean pressure to increase its power density. A thermoacoustic cooler is also added to the engine as an acoustic load so that the thermal efficiency can be evaluated numerically. Finally, the pros and cons of this bypass configuration are analysed and discussed.

2. Modelling and simulations of a bypass engine

A travelling wave thermoacoustic engine with the bypass

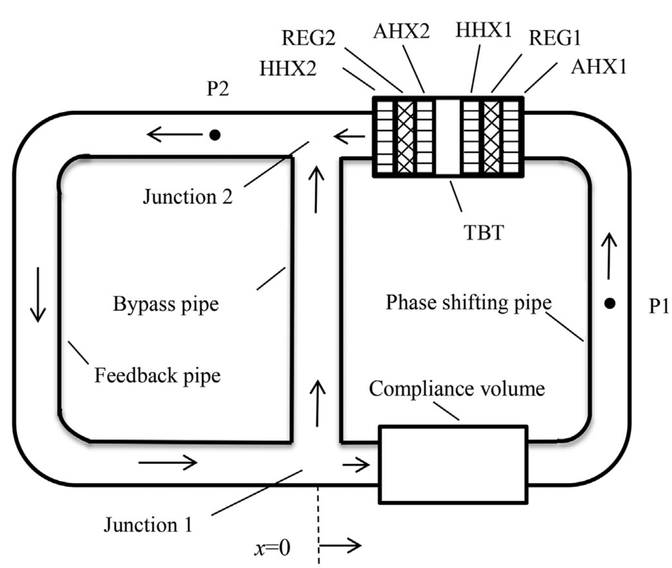

Fig. 1. Schematic diagram of a travelling wave thermoacoustic engine with a bypass configuration [1]. The arrows indicate the direction of the acoustic power flow according to the simulations presented later in this paper. HHX: hot heat exchanger, REG: regenerator, AHX: ambient heat exchanger, TBT: thermal buffer tube.