Applied Energy 231 (2018) 372–379

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Low-temperature energy conversion using a phase-change acoustic heat engine

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HIGHLIGHTS

- Modified thermoacoustic engine can recover heat at temperatures < 100 °C.
- A condensable vapor is added to the working fluid, improving engine performance.
- The engine operates at temperature differences as low as 30 K.
- Acoustic work increases by as much as a factor of 8.

ARTICLE INFO

Keywords:
Thermoacoustics
Low temperature
Waste heat recovery
Solar energy
Phase change

ABSTRACT

Low-temperature heat is abundant, accessible through solar collectors or as waste heat from a large variety of sources. Thermoacoustic engines convert heat to acoustic work, and are simple, robust devices, potentially containing no moving parts. Currently, such devices generally require high temperatures to operate efficiently and with high power densities. Here, we present a thermoacoustic engine that converts heat to acoustic work at temperature gradients as low as ~4–5 K/cm, corresponding with a hot-side temperature of ~50 °C. The system is based on a typical standing-wave design, but the working cycle is modified to include mass transfer, via evaporation and condensation, from a solid surface to the gas mixture sustaining the acoustic field. This introduces a mode of isothermal heat transfer with the potential of providing increased efficiencies – experiments demonstrate a significant reduction in the operating temperature difference, which may be as low as 30 K, and increased output – this 'wet' system produces up to 8 times more power than its dry equivalent. Furthermore, a simplified model is formulated and corresponds quite well with experimental observations and offering insight into the underlying mechanism as well as projections for the potential performance of other mixtures. Our results illustrate the potential of such devices for harvesting energy from low-temperature heat sources. The acoustic power may be converted to electricity or, in a reverse cycle, produce cooling – providing a potential path towards solar heat-driven air conditioners.

1. Introduction

Low-temperature heat, abundantly available as solar radiation or industrial exhaust streams, is still a largely underutilized energy source. For example, the US manufacturing sector rejects approximately 15 GW of technical potential as waste heat every year [1]. However, converting heat to mechanical energy at low temperatures is inherently inefficient, as dictated by thermodynamics. Therefore, energy conversion devices intended for use under these conditions should ideally be designed to be inexpensive and modular, capable of economical implementation in small scale applications, e.g., at the single dwelling. Within this context, several emerging technological solutions can be considered. Thermoelectric generators offer high reliability, low weight and simplicity, yet its use has been mostly limited to extreme environments due to high material costs. Recent advances have shown potential for cost reduction, but thermal efficiency will likely still be limited to about 20% of Carnot within the next several years [2]. Organic Rankine Cycle (ORC) technology is more mature, and has been widely applied commercially for biomass combustion, industrial waste heat recovery, and geothermal energy. However, downscaling it to the order of several KW currently increases its cost significantly, making it uneconomical for small scale applications [3]. Sorption refrigeration

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https://doi.org/10.1016/j.apenergy.2018.09.124
Received 24 April 2018; Received in revised form 9 September 2018; Accepted 10 September 2018

research is currently focused on decreasing system costs and increasing the coefficient of performance, which is typically below 1 for temperatures under 100 °C [4]. Thus, tapping low-temperature heat, particularly at small scales, remains an important, as yet unresolved, engineering challenge.

Thermoacoustic engines are energy conversion devices, in which pressure oscillations within an acoustic field mediate heat flow and work production. These devices are unique in that they contain no moving mechanical parts or exotic materials, consequently exhibiting great potential for reliability and low-cost [5]. The acoustic power produced using heat, may then be converted into electricity or used in a reversed cycle, for cooling [5]. Thermoacoustic engines were first developed in a standing-wave configuration, which, while simple and straightforward, is characterized by an inherent irreversibility associated with the imperfect thermal contact between gas and solid, necessary for the engine's operation [6]. The greatest breakthrough, to date, has been the realization of a travelling-wave configuration, with a significantly improved efficiency [7]. This configuration has since been developed, and devices with a power output greater than 1 kW have been reported [8,9]. These devices, however, typically operate at high temperatures ($>$ 550 °C), and suffer from considerable losses in the regenerator [10]. Recent designs have been shown to operate at relatively low temperatures of 100–200 °C [11]; however, at such low temperatures the power density drops substantially. Hence, further improvement is required, if low-temperature operation is to be accomplished effectively.

The presence of a condensable vapor on the solid, porous substrate (the 'stack') can offer potential improvements over the 'classical' thermoacoustic cycle. A 'classical' thermoacoustic instability relies on heat conduction between the working fluid (gas) and the solid [5]. In the system reported here, the cycle is augmented with mass transfer (a conceptualization of the mechanism is shown in Fig. 1). When the gas is displaced and compressed, and dependent on the local equilibrium between the gas and liquid, mass is transferred. If the gas partial pressure is lower than the equilibrium value, mass will be released into the mixture – as in the power stroke of an engine. During the expansion stage, mass will be deposited, despite the lowered pressure, if dictated by the local equilibrium (due to a lower ambient temperature, for example). Heat may still be exchanged in the process by the conductive mode but, more importantly, so is the latent heat of the phase-change process, which can be far greater. Raspet et al. [12] showed theoretically that in such a configuration, pressure oscillations may be triggered at reduced temperatures, due to the altered nature of heat transfer between the gas and solid, now governed by phase change rather than conduction. The same theoretical conclusion was recently realized by Yasui and Izu [13] by applying classical thermoacoustic linear theory in a Lagrangian simulation of a single humid air parcel. These ideas were experimentally demonstrated in recent years by Noda and Ueda [14], who demonstrated the phenomenon on a thermoacoustic engine powered by vaporized water and ethanol, and Kawaminami et al. [15] who improved this evaporator engine by changing the resonator geometry. Tsuda and Ueda have shown that at a certain humidity rate, the temperature of acoustic onset is abruptly reduced, remaining constant for any higher humidity value [16] and also measured the temperature gradient required to initiate self-sustained oscillations in standing and travelling-wave acoustic configurations with a wetted stack, as opposed to the previous evaporator-type designs [17]. Nevertheless, acoustic oscillations in this wetted-stack configuration could not be maintained due to the loss of water to evaporation, while it is still not clear how to recirculate the water without flooding the stack in higher powered evaporator-type engines.

Herein, we report the first successful steady operation of an acoustic engine exhibiting augmented performance due to the presence of evaporation and condensation, in a closed system with a wetted stack and fluid regeneration. In the studied configuration, the repeated phase change of water at the surface of the stack, and resultant improved solid-gas heat exchange, allow it to simultaneously reduce the required temperature gradient and increase the power density, thus addressing two significant drawbacks of current systems. While we also measure the conditions leading to onset of oscillations, as recently reported by Tsuda and Ueda [17], the main step forward performed in the current study is the ability to assess the real power output of steady operation, compared with an identical system where phase-change is absent. Our engine demonstrates a significant reduction, by a factor of 2–3, of the temperature differential required to maintain acoustic oscillations, while also increasing the acoustic output. Furthermore, the mechanism

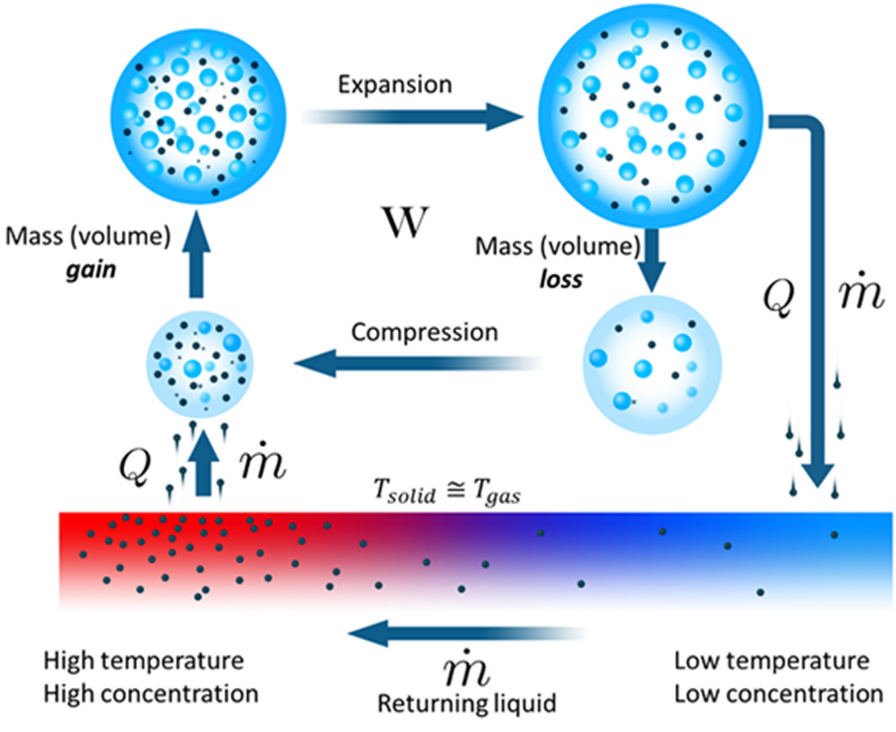

Fig. 1. Conceptualized mechanism of 'phase-change' thermoacoustics. The resonator contains a binary mixture comprising an inert and a 'reactive' component (air and water, respectively, in our experiment) that undergoes reversible sorption with the solid sorbent 'stack' (or, possibly, evaporation/condensation). Gas motion is accompanied by pressure variations that execute a thermodynamic cycle: compression occurs during motion towards the hot end where, due to the heating (using low-temperature solar or waste heat), equilibrium conditions favor desorption and the reactive component is released into the gas mixture, causing it to expand at high pressure – a power stroke. During the second half-cycle, the gas expands as it moves to the cold side, where mass is lost due to sorption, once again performing work on the gas as it contracts at low pressure. This cycle produces acoustic power. In our system, liquid water travels back within the stack walls by capillary action and gravity.