ARTICLE IN PRESS

Applied Energy xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Critical temperature of traveling- and standing-wave thermoacoustic engines using a wet regenerator

Kenichiro Tsuda *, Yuki Ueda

Tokyo University of Agriculture and Technology, 2-24-16 Nakacho, Koganei, Tokyo 184-8588, Japan

HIGHLIGHTS

- The reduction in the critical temperature by adding water is investigated.
- The reduction is observed in standing- and traveling-wave thermoacoustic engines.
- The reduction is obtained when the material composing the regenerator is changed.
- The critical temperature was decreased from over 900 °C to below 100 °C.

ARTICLE INFO

Article history:
Received 17 November 2016
Received in revised form 27 March 2017
Accepted 1 April 2017
Available online xxxx

Keywords:
Thermoacoustics
Low-grade heat
External-combustion engine
Water

ABSTRACT

When the temperature of the hot end of the regenerator in a thermoacoustic engine exceeds a critical value, spontaneous gas oscillation occurs. In this study, we experimentally investigated the reduction of this critical temperature by adding water to the regenerator. Three thermoacoustic engines (TAEs) were constructed. The first was a standing-wave TAE with a straight tube, the second a traveling-wave TAE with a looped tube, and the third a traveling-wave TAE with both looped and straight tubes. Two types of regenerator were used, made from stacked stainless-steel mesh screens and from ceramics. The radius of the flow channel was also varied. The results showed that the use of a wet regenerator dramatically reduced the critical temperature in all three TAEs, and that this reduction was obtained with both types of regenerator material. These indicate the possibility for operating TAEs with low-grade wasted heat. Furthermore, it was found that when a dry regenerator was replaced by a wet one, the dependence of the critical temperature on the flow channel radius became weaker, but it was still possible to set an optimum radius for lowering the critical temperature.

1. Introduction

When one end of a tube is heated and the other end is cooled, gas inside the tube may begin to spontaneously oscillate, resulting in the excitation of an acoustic wave. When the acoustic wave is excited, heat flow is converted to acoustic power flow [1–3]. This phenomenon is caused by the thermal interaction between the gas and the wall of the differentially heated tube, and is utilized in a thermoacoustic engine (TAE).

A TAE usually comprises waveguides and a differentially heated regenerator. The regenerator has many narrow flow channels and is sandwiched between hot and cold heat exchangers. Three types of TAEs have been developed, as shown in Fig. 1: a standing-wave TAE with a straight tube, a traveling-wave TAE with a looped tube, and a traveling-wave TAE with both looped and straight tubes. For energy conversion, the standing-wave TAE utilizes intrinsically irreversible thermal contact between the regenerator wall and the working gas, limiting its thermal efficiency [4–7]. One of the most powerful standing-wave TAEs, which was constructed by Swift, achieved a thermal efficiency of 9% [8] and it has been pointed out that the efficiency of standing-wave TAEs is limited to less than 20% [9]. In contrast to the standing-wave one, the traveling-wave TAE uses thermal contacts that are inherently reversible, allowing greater efficiencies to be achieved [5–7,10]. Backhaus and Swift and Tijani et al. constructed the efficient traveling-wave TAEs having thermal efficiencies reaching 30%, which are comparable to the efficiency of a conventional car engine [6,11,12].

The TAEs can be driven with a wide variety of heat sources because they are external combustion engines. Furthermore, they can have high reliability and a long lifetime because of the absence of moving parts. These characteristics make TAEs, especially traveling-wave TAEs, suitable for use in waste-heat recovery [13–17] and sunlight-driven systems [18].

* Corresponding author.
E-mail address: s141144x@st.go.tuat.ac.jp (K. Tsuda).

http://dx.doi.org/10.1016/j.apenergy.2017.04.004
0306-2619/

Please cite this article in press as: Tsuda K, Ueda Y. Critical temperature of traveling- and standing-wave thermoacoustic engines using a wet regenerator. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.04.004

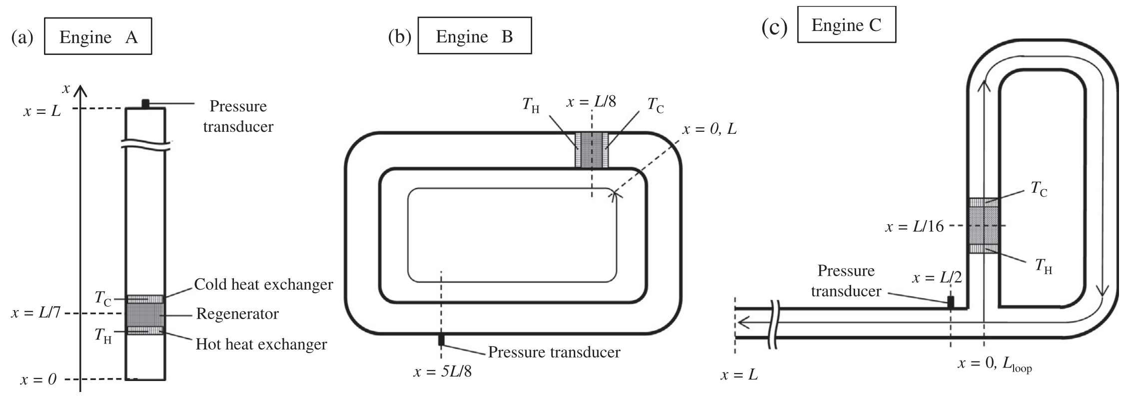

Fig. 1. Constructed thermoacoustic engines. (a) Standing-wave thermoacoustic engine with a straight tube, (b) traveling-wave thermoacoustic engine with a looped tube, (c) traveling-wave thermoacoustic engine with looped and straight tubes.

To induce spontaneous gas oscillation, the temperature at the hot end of the regenerator, T_H, must exceed a critical temperature when the temperature at the cold end of the regenerator, T_C, is kept constant. Many conventional TAEs have critical temperatures of several hundred °C, when T_C is maintained at ambient temperature. To utilize waste heat, a TAE must have a critical temperature lower than that of the waste heat, which in many cases is below 200 °C [19]. This suggests that reducing the critical temperature to below 200 °C will greatly increase the usefulness of the TAE design [13,14].

Recently, multi-stage traveling-wave TAEs that have some regenerators have been developed as low-temperature-heat driven engines. Biwa et al. [13] installed five regenerators into the traveling-wave TAE which had straight and looped tubes, and demonstrated that the critical temperature is reduced from 227 °C to 57 °C. de Blok [14] constructed the looped tube traveling-wave TAE having four regenerators and realized the critical temperature of 50 °C. These TAEs have been investigated to drive a electric generator or a thermoacoustic heat pump.

Rayleigh [20] discussed the use of water to reduce the critical temperature in his book "The Theory of Sound." Raspet et al. [21] developed the theory of acoustic propagation in a gas-condensing vapor enclosed within a narrow tube, and demonstrated a reduction in the critical temperature from 297 °C to 97 °C by using water. Noda and Ueda [22] demonstrated a reduction in the critical temperature from 316 °C to 82 °C in a TAE powered by boiling water. In a previous study [23], we constructed a TAE like that shown in Fig. 1(a), and identified the threshold value of the water volume needed to reduce the critical temperature. These results imply the possibility that a constructed efficient TAE having a relative high critical temperature can be improved for a low-temperature-waste-heat recovery system by only adding water. However, all the TAEs that have been used to investigate the effect of water are of the standing-wave type, although the traveling-wave TAE can achieve a higher efficiency than the standing-wave TAE. Furthermore, the reason why water contributes to the reduction in the critical temperature has been still unclear.

There are two difference points between standing- and traveling-wave TAEs. One is the shape of tubes comprising TAEs as shown in Fig. 1 and the other is the flow channel radius in regenerators. The shape of tubes determines the feature of the acoustic wave excited in the tubes and the flow channel radius largely affects the thermal process in regenerators. In this study, we constructed three types of TAEs shown in Fig. 1 and measured their critical temperature with varying the flow channel radius under two conditions: one in which the working gas was dry air, and the other in which water was added to the working gas. Furthermore, the effect of the martial composing the regenerators were investigated. It was observed that when water was added, the critical temperatures of all the three TAEs were dramatically reduced, and that the reduction in the critical temperature was independent of the radius and the material of the regenerator. This makes it possible to construct a low-grade wasted-heat-driven traveling-wave TAE. To address the mechanism how water reduces the critical temperature, we analyzed the experimental results using Raspet's theory [21].

2. Experimental setup

We constructed the three thermoacoustic engines shown in Fig. 1. The first engine (Engine A, Fig. 1(a)) has a straight tube with two ends. In this design, a standing acoustic wave contributes to the energy conversion [5–7]. The second engine (Engine B, Fig. 1 (b)) has a looped tube. This design can use both standing and traveling acoustic waves for energy conversion [5]. The third engine (Engine C, Fig. 1(c)) has a looped tube and a straight tube. In this design, most of the energy conversion is contributed by the traveling wave.

A 40 mm-long regenerator was inserted into a stainless-steel tube with an inner diameter of 40 mm. As noted in the introduction, thermal interaction between the regenerator wall and the working gas initiates spontaneous gas oscillation. This thermal interaction can be controlled by a dimensionless parameter, $\omega\tau_\alpha$, where ω is the angular frequency and τ_α is the thermal relaxation time expressed by the characteristic length of the regenerator, r, and the thermal diffusivity of the working gas, α. The thermal relaxation time is then given by $\tau_\alpha = r^2/2\alpha$. When $\omega\tau_\alpha \ll 1$, there is good thermal contact between the gas and the regenerator wall, allowing thermodynamic reversibility, whereas when $\omega\tau_\alpha \gg 1$, the thermal contact is lost. Thermal contact becomes irreversible when $\omega\tau_\alpha \sim 3$ [5–7]. The critical temperature depends on the value of $\omega\tau_\alpha$, which, by definition, can be controlled by r. We therefore used regenerators with lengths r ranging from 0.042 mm to 1.1 mm, as listed in Table 1. The regenerators were made either from honeycomb ceramic or from multiple stainless-steel wire mesh screens. As the honeycomb ceramic has many square channels, we defined the length r as half of one side of the square. The length r of the stainless-steel wire mesh screens was defined by the equation $r = (D_h \times d)^{0.5}/2$, where D_h and d are the hydraulic diameter and the diameter of the screen wire, respectively [24]. The calculated values of $\omega\tau_\alpha$ are shown in Table 1 and are discussed below.

10 mm-long hot and cold heat exchangers were placed at either end of the regenerator. They were made of flat brass plates 1 mm in thickness, set in parallel at intervals of 2 mm. The temperatures of the working gas in the hot and cold heat exchangers were denoted

Please cite this article in press as: Tsuda K, Ueda Y. Critical temperature of traveling- and standing-wave thermoacoustic engines using a wet regenerator. Appl Energy (2017), http://dx.doi.org/10.1016/j.apenergy.2017.04.004