EFFECT OF FLOW CHANNEL RADIUS ON THE ENERGY CONVERSION OF THERMOACOUSTIC MACHINE FOR DIFFERENT AMBIENT TEMPERATURE

by

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This study investigates the influence of ambient temperature on the energy conversion performance of a thermoacoustic engine operating with air at atmospheric pressure. A looped-tube thermoacoustic engine model was developed and analyzed using finite element simulations. The primary parameter of interest was the ambient (cold-side) temperature, which was varied systematically to represent cold (−18 °C), moderate (28 °C), and hot (45 °C) environmental conditions, and to evaluate its impact on onset conditions, acoustic power generation, and overall efficiency. Results show that smaller flow channel radii, particularly 0.27 mm, yields the highest performance across all ambient temperature scenarios due to enhanced acoustic impedance and pressure amplification. At this radius, both exergy and energy efficiency are the highest under hot ambient conditions, reaching 61 % and 23 %, respectively, although the system requires higher hot-side temperatures for operation. These findings highlight the importance of optimizing flow channel geometry for efficient thermal-to-acoustic energy conversion under realistic environmental conditions. The study provides a foundation for designing thermoacoustic engine adaptable to diverse climates and practical waste-heat recovery applications.

Keywords: *thermoacoustic engine, energy conversion, ambient temperature, flow channel radius, waste-heat recovery, acoustic impedance.*

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Introduction

Global energy outlooks indicate that the global energy system is undergoing a transition in which renewable energy deployment and climate policies are key drivers in reducing fossil fuel dependency [1]. Global energy demand has been steadily increasing due to industrial growth, urbanization, and population expansion. To mitigate the environmental consequences of fossil fuel dependence, there has been a significant push toward renewable and sustainable energy technologies. According to the International Energy Agency (IEA), renewable sources are expected to account for nearly 42% of global electricity generation by 2030, with solar and wind leading this transition [1]. However, the efficiency of current energy conversion systems remains limited, as a large fraction of input energy is wasted as low-grade heat in industrial processes and power generation. Harnessing this untapped thermal resource is therefore critical for improving overal system efficiency and reducing carbon emissions [1]. On the other hand, there are other issues related to waste heat as consequence of industrial activities. Therefore, waste heat recovery is essential [1].

Conventional waste-heat recovery methods, such as organic Rankine cycles or thermoelectric systems, are often restricted by scale, cost, and efficiency, particularly at low temperature ranges. This has motivated the exploration of alternative technologies capable of directly converting low-grade heat into useful power. Among these, thermoacoustic engines (TAE) have attracted increasing attention in recent decades. The TAE operate based on the thermoacoustics effect, where a temperature gradient applied across a porous medium (stack or regenerator) inside a resonator induces acoustics oscillations [2]. These oscillations can then be harvested for power generation or refrigeration applications. Their key advantage include mechanical simplicity [3], absence of moving parts, low maintenance, and the ability to utilize environmentally benign working fluids such as helium or nitrogen. The waste heat can be utilized for generating thermoacoustics power in an engine [4-6]. Then, the power is used for electrical power generation and refrigeration [7-12].

Research has demonstrated the versality of TAE in harnessing waste heat from diverse sources. For instance, practical implementations have successfully utilized waste heat from industrial ovens, biomass combustion, and even solar-thermal collectors [4, 13]. In automotive applications, modelling studies have shown that TAE can potentially convert waste heat from diverse sources. For instance, practical implementation exhaust heat into acoustic power with meaningful efficiency gains, offering a pathway for onboard energy recovery [4]. Despite these advancements, most studies evaluate TAE under fixed laboratory conditions, often neglecting the role of external environmental parameters.

The performance of the engine is important to be investigated by considering parameters. Several parameters influence the engine efficiency [14-16]. Farikhah *et. al*. [11] reported that there is an impact of gas mean pressure on the efficiency. They found that the performance of the engine increases when the mean pressure elevates. In addition, Utami *et. al*. [17] performed the numerical computation of the flow channel radius on the efficiency of a TAE. The radius has a huge impact on the total efficiency of the system [7]. In Rokhmawati *et al*. [15] carried out a numerical study of loop radius on the efficiency of thermoacoustics and found that the loop radius has an impact on improving energy conversion in the engine. Cricially, the stack length is a fundamental design parameter. Farikhah *et al*. [16] found that the optimal stack length for the thermoacoustics engine was 6 cm, yielding a peak efficiency of 27%. They concluded that this maximum performance occurs because a 6 cm stack length maximizes acoustic impedance while minimizing acoustic velocity, thereby reducing energy losses in the

system. Recent work has further highlighted how optimization of geometrical parameters, such as stack length, radius, and porosity can significantly influence onset temperature, acoustic power generation, and overall system efficiency [6, 8]. For example, according to Farikhah *et al*. [5], the highest total efficiency (η_2, total) achieved for the 4-stage TAE was 8% of the Carnot limit when the dimensionless stack radius ratio (r/δ) was optimized to 1.2. This efficiency was attained at a very low onset heating temperature of 43 °C, making the system highly suitable for utilizing low-grade waste heat sources. Similarly, based on the study by Farikhah *et al*. [14], the optimal stack diameter for maximizing the efficiency of the TAE was found to be 2 cm, resulting in an engine efficiency of 36%. This efficiency is nearly twice that achieved with more common stack diameters, such as 5 cm.

Ambient temperature is a particularly critical factor influencing TAE performance. Since the driving mechanism of TAE depends on the temperature difference between the hot and cold heat exchangers, variations in ambient (cold-side) temperature directly affect onset conditions, oscillation stability, and overall efficiency. In practice, these ambient variations are inevitable, as TAE may be deployed in diverse climates ranging from cold regions to hot desert environments. Previous studies on thermal machines have highlighted how ambient conditions can alter conversion efficiency and operational stability, yet systematic investigations into their impact on thermoacoustic systems remain limited. For example, Farikhah and Ueda [18] analyzed the role of channel radius on coupled TAE -cooler systems, showing how boundary conditions influence efficiency, while subsequent work demonstrated that stack length and ambient-side variations play a substantial role in dictating energy conversion performance.

Farikhah and Ueda [18] studied the effect of regenerator radius on the efficiency of a heat-driven thermoacoustic cooler. However, the setting cooling temperature was extremely low at about 251 K and it was lack of elucidation of the acoustic field characterization and mechanism. It was found that the optimum regenerator radius is 1 [18]. We consider that the optimum radius would shift when the cooling temperature is set at 273 K. Therefore, the effect of the radius on the performance of the thermoacoustics refrigerator driven by prime mover and the characteristics of the acoustic field is invesigated for cooling temperature 273 K.

It is important to note that this study, like many high performance thermoacoustic models, utilizes helium at a high pressure of 3 MPa to achieve high efficiency. This requirement for high pressure containment adds significant complexity, cost, and engineering challenges to the system's installation and maintenance. However, for practical applications, particularly in rural or resource-limited areas, the use of ambient air as a working fluid is highly desirable due to its simplicity, availability, and zero cost. Future work should therefore focus on adapting these design optimizations for systems operating with air at or near atmospheric pressure, despite its lower thermodynamic performance compared to helium, to enhance the accessibility, safety, and deployment of this technology. However, there are no investigations about varying ambient conditions with different flow channel radius. Therefore, it is essential to carry out these investigation. This gap motivates the present work, which aims to analyze the effect of varying ambient temperatures and the effect of flow channel radius on the energy conversion performance of TAE. The objectives of this study are to simulate the influence of different ambient-side boundary conditions on the engine performance. By addressing this underexplored dimension, the study contributes to the advancement of TAE as practical and adaptable solutions for renewable and waste-heat recovery applications.

Method

Calculation model

The TAE was modeled using a looped-tube configuration that included a single stack and heat excahngers, fig. 1(a). The looped tube had a total length of 2.8 m, with a tube radius of 20 mm. The stack, represented as an array of thin circular channels, had a diameter of 4 cm and a pore radius of 0.3 mm. The working fluid is air at 0.1 MPa. The stack was positioned between the stability limit calculation. To improve thermal stability, a 600 mm thermal buffer tube was placed adjacent to the hot heat exchanger. The primary variable under investigation was the ambient temperature, which was systematically varied to evaluate its effect on system performance. Specifically, three ambient temperature scenarios were considered: cold (−18 °C), moderate (28 °C), and hot (45 °C). These values represent typical environmental conditions that a TAE may encounter and allow for a comparative evaluation of engine performance across diverse climates.

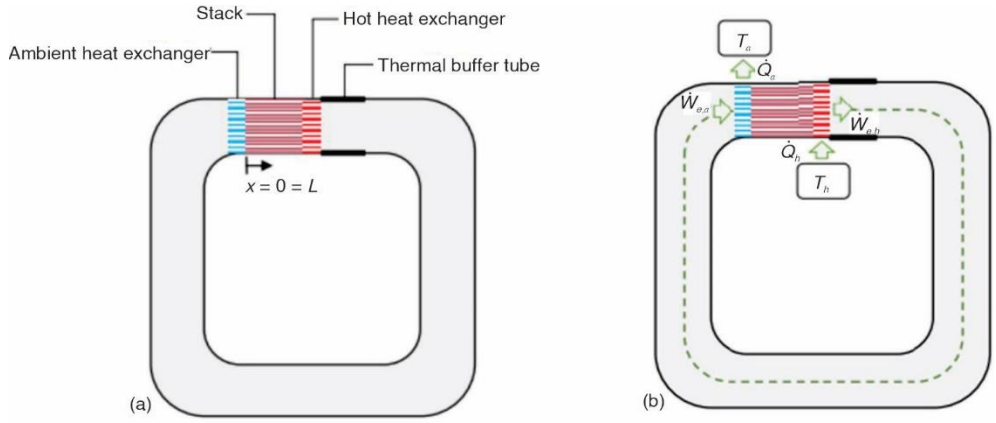

Figure 1. (a) Schematic illustration of thermoacoustic system engine and (b) thermodynamic schematic illustration

Evaluated efficiency

In thermoacoustics engine, thermal energy is transformed into acoustic energy, making it a key factor in evaluating efficiency. The determination of effciency depends on the acoustic power generated, which results from the conversion of heat input, Q_h, into acoustic acoustic output, W_{ac}. Both Q_h and W_{ac} are formulated in terms of the oscillatory pressure, P, and velocity, U, as described [19, 20]:

$$\dot{W} = \frac{A}{2}\mathrm{Re}\left[P\tilde{U}\right] \tag{1}$$

$$\dot{Q} = \frac{A}{2}\mathrm{Re}\left[P\tilde{U}\left(\frac{\tilde{\chi}_v - \chi_\alpha}{(1+\sigma)(1-\tilde{\chi}_v)}\right)\right] - \frac{A\rho_m c_p |U|^2}{2\omega(1-\sigma^2)|1-\chi_v|^2} Im\left[\chi_\alpha + \sigma\tilde{\chi}_v\right]\frac{\mathrm{d}T_m}{\mathrm{d}x} \tag{2}$$

where x is the axial position along the tube, T_m – the time-averaged gas temperature, A – the tube's cross-sectional area, and the tilde symbol denote the complex conjugate. In addition, χ_v, χ_α, ρ_m, σ, γ, c_p correspond to the spatially averaged viscous function, thermal function,

mean density, Prandtl number, specific heat at constant pressure, and the specific heat ratio, respectively.

Figure 1(b) presents the thermoacoustic enegine system from a thermodynamic perspective. The term $\dot{W}_{e,A}$ represent the acoustic power at the ambient end of the engine stack. Once the temperature exceeds a certain threshold, the working fluid within the stack and tube begins to oscillate, generating acoustic wave in the stack that propagates through the tube. As a result, acoustic energy is transported along the tube, originatng at the ambient end of the stack. Within the stack, this power is amplified, and the corresponding increase in acoustic power, $\Delta\dot{W}_e$ and the heating power, $\dot{Q}_h$, is delivered to the hot heat exchanger, and the engine efficiency can be expressed as:

$$\eta_e = \frac{\Delta\dot{W}_e}{\dot{Q}_h} \tag{3}$$

$$\Delta\dot{W}_e = \dot{W}_{e,h} - \dot{W}_{e,a} \tag{4}$$

To evaluate the obtain, η_e, against its thermodynamic maximum, the efficiency is expresses as:

$$\eta_{2,e} = \frac{\eta_e}{\eta_{\text{Carnot}}} \tag{5}$$

Where the thermodynamically maximal value can be written as:

$$\eta_{\text{Carnot}} = \frac{T_h - T_a}{T_h} \tag{6}$$

where T_h and T_a are the temperatures of the stack engine at the hot and ambient ends, respectively.

Results and discussion

Thermoacoustic engine for cool ambient temperature

Figure 2 shows the variation of engine efficiency with the flow channel radius for three ambient temperature conditions, namely hot (45 °C), moderate (28 °C), and cold (18 °C). Three types of efficiencies are presented: energy efficiency, exergy efficiency, and the corresponding Carnot efficiency. For all ambient temperature conditions, the exergy efficiency is the highest, followed by the Carnot efficiency, while the energy efficiency exhibits the lowest values. A clear decreasing trend is observed for all efficiencies as the flow channel radius increases from 0.27 mm to 0.42 mm, indicating that enlarging the flow channel radius degrades the thermodynamic performance of the TAE. In addition, at a given radius, the hot condition (45 °C) consistently yields the highest efficiency, followed by the moderate (28 °C) and cold (18 °C) conditions. The highest energy efficiency and exergy efficiency are obtained at the smallest flow channel radius of 0.27 mm under the hot ambient temperature condition, reaching approximately 23% and 62%, respectively. This result suggests that smaller flow channels enhance the thermoacoustic energy conversion process and that higher ambient temperatures provide more favorable operating conditions for the TAE.

Figure 3 illustrates the variation of the heating temperature with the flow channel radius for three ambient temperature conditions, namely hot (T_a = 45 °C), moderate (T_a = 28 °C), and cold (T_a = 18 °C). It can be observed that, for all ambient conditions, the required

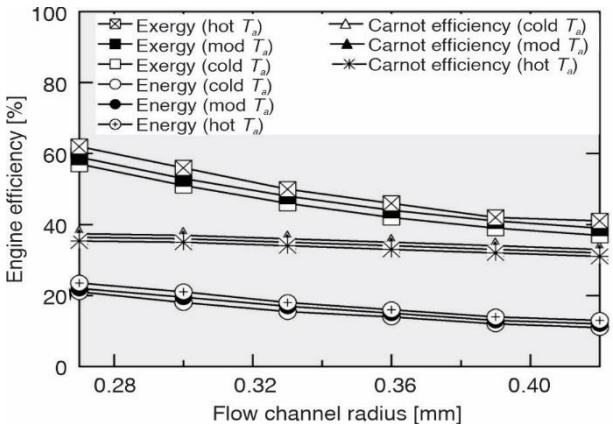

Figure 2. Flow channel radius *vs.* engine efficiency

heating temperature decreases gradually as the flow channel radius increases from about 0.27 mm to 0.41 mm. At any given flow channel radius, the heating temperature under the hot ambient condition is the highest, followed by the moderate and cold ambient conditions. The maximum heating temperature is obtained at the smallest flow channel radius of 0.27 mm, while a nearly monotonic reduction is observed with increasing radius. This trend indicates that enlarging the flow channel reduces the required heating temperature for engine operation, whereas higher ambient temperatures demand higher heating temperatures to maintain the TAE performance.

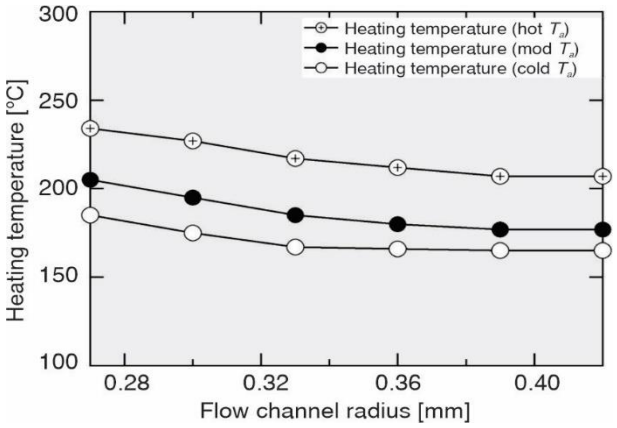

Figure 3. Flow channel radius *vs.* heat temperature

Figure 4 shows the variation of acoustic power and heating power with the flow-channel radius for cold (18 °C), moderate (28 °C), and hot (45 °C) ambient temperatures. In the present analysis, a lower heating power requirement and a higher generated acoustic power are considered favourable. As the flow-channel radius increases, the heating power generally increases for all ambient conditions, whereas the acoustic power gradually decreases. This opposite trend indicates a clear trade-off between the required heating input and the produced acoustic output. For all three ambient temperatures, the smallest flow-channel radius (0.27 mm) provides the most desirable performance, since it simultaneously yields the highest acoustic power and the lowest heating power. Therefore, considering both criteria, namely maximizing

acoustic power while minimizing heating power, a flow-channel radius of 0.27 mm can be identified as the optimum configuration for the present thermoacoustic system.

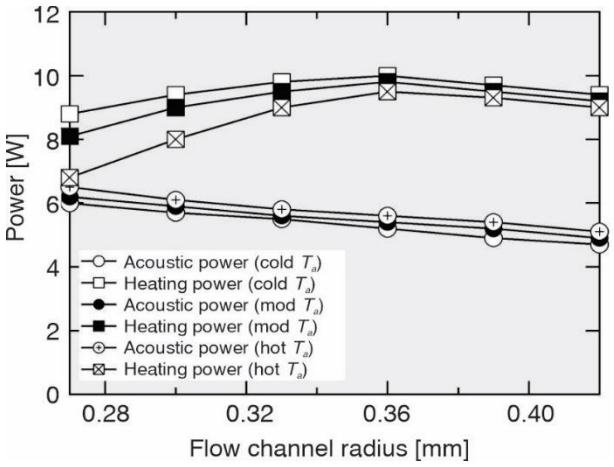

Figure 4. Flow channel radius *vs.* power

Figure 5 shows the dependence of acoustic impedance on flow channel radius for cold, moderate, and hot ambient temperature. In all cases, acoustic impedance decreases as the channel radius increases, indicating that smaller channels promote higher impedance. Among the three conditions, the hot ambient temperature case consistently exhibits the highest impedance, followed by moderate and cold ambient temperature, demonstrating the strong influence of elevated temperature on enhancing impedance through increased thermo-viscous interactions. From a design perspective, the results indicate that higher acoustic impedance can be achieved by employing smaller flow channels and operating at higher temperatures, which is beneficial for improving acoustic power transfer and energy conversion effectiveness in thermoacoustic stacks or regenerators.

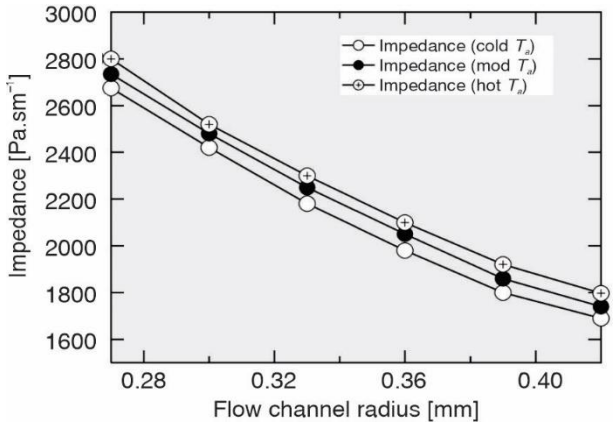

Figure 5. Flow channel radius *vs.* impedance

Figure 6 shows that at smaller flow channel radii, the acoustic pressure component is relatively high, which is associated with increased acoustic impedance and stronger pressure oscillations – favorable for thermoacoustic energy conversion. In contrast, the velocity behavior at small radii is characterized by lower velocity amplitudes, which is directly linked

to reduced viscous losses. Lower velocity limits shear near the channel walls and suppresses viscous dissipation within the boundary layers. As the channel radius increases, velocity rises due to reduced flow resistance, but this comes at the cost of increased viscous losses. Therefore, while pressure benefits from smaller radii through higher impedance, velocity benefits in a different way: low velocity in narrow channels is advantageous because it minimizes viscous losses, which is crucial for maintaining high thermoacoustic efficiency.

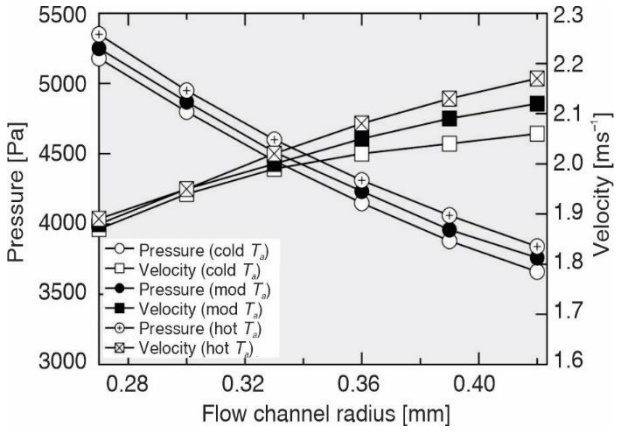

Figure 6. Flow channel radius *vs.* pressure

Conclusions

This study systematically investigates the impact of flow channel radius in different ambient temperatures on the energy conversion performance of a looped-tube TAE using air at atmospheric pressure. The key findings are as follows.

- *Optimal flow channel radius*: A flow channel radius of 0.27 mm consistently yields the highest performance across all ambient temperature conditions: cold (−18 °C), moderate (28 °C), and hot (45 °C). This is due to enhanced acoustic impedance, pressure amplification, and low fluid velocity, which maximize the conversion of thermal energy into acoustic power.
- *Efficiency metrics*: The system achieves its peak exergy efficiency of 62% under hot ambient conditions (45 °C), compared to 59% under moderate (28 °C) and lower values under cold conditions (−18 °C). Energy efficiency also reaches its maximum of 23% at the hot ambient temperature, indicating that heat-to-work conversion is most effective in hotter climates.
- *Trade-off with hot-side temperature*: While smaller flow radii significantly improve efficiency, they require higher hot-side temperatures to initiate and sustain thermoacoustic oscillations, representing a key operational trade-off.
- *Environmental adaptability*: By optimizing geometric parameters such as the flow channel radius, TAE can maintain high performance across diverse environmental conditions, making them highly suitable for practical waste-heat recovery applications in a variety of climates.

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