Research Paper

Numerical Study on the Effect of Mean Pressure and Loop's Radius to the Onset Temperature and Efficiency of Traveling Wave Termoacustic Engine

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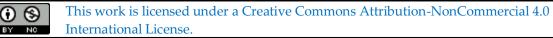
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Abstract

The thermoacoustic engine can be a device to convert waste heat energy in the engine car become useful energy such as for charging battery in car or Air conditioner of the car. This work can be done by experimentally and numerically. There are some parameters that have an impact on the performance of the engine. They are geometry of the engines, working fluid, and mean pressure. The performance of the engine depends on the efficiency and the heating temperature. In the car, waste heat energy is not high enough. Therefore, we need to utilize the low heating temperature to be converted into useful energy. This study contributes to numerically the effect of mean pressure and loop's radius of the regenerator on the onset temperature and the efficiency of traveling wave thermoacustic engines. The application that is used to solve numerical problems is fortran95. There are two codings that are used in fortran95. They are stability limits and efficiency codes. The lowest onset temperature that achieved is 153°C with efficiency up to 38.1% that can be reached when the mean pressure is 4.0 MPa and the loop's radius is 5 cm. This result indicated that we can use low heating temperatures from waste heat of engine car to turn on electronics equipment inside the car.

Keywords: Mean pressure; Loop's radius; Thermoacoustic engine

Abstrak

Mesin thermoacoustic dapat menjadi alat untuk mengubah energi panas buangan pada mesin mobil menjadi energi yang berguna seperti untuk pengisian aki di mobil atau AC mobil. Pekerjaan ini dapat dilakukan secara eksperimental dan numerik. Ada beberapa parameter yang berdampak pada performa mesin. Mereka adalah geometri mesin, fluida kerja, dan tekanan rata-rata. Performa mesin tergantung pada efisiensi dan suhu pemanasan. Di dalam mobil, energi panas terbuang tidak cukup tinggi. Oleh karena itu, kita perlu memanfaatkan suhu pemanasan rendah untuk diubah menjadi energi yang berguna. Studi ini berkontribusi secara numerik untuk pengaruh tekanan rata-rata dan radius loop regenerator pada suhu awal dan efisiensi mesin termoakustik gelombang berjalan. Aplikasi yang digunakan untuk memecahkan masalah numerik adalah fortran95. Ada dua kode yang digunakan di fortran95. Mereka adalah batasan stabilitas dan kode efisiensi. Onset temperature terendah yang dicapai adalah 153°C dengan efisiensi hingga 38,1% yang dapat dicapai pada tekanan rata-rata 4,0 MPa dan radius loop 5 cm. Hasil ini menunjukkan bahwa kita dapat menggunakan temperatur pemanasan rendah dari limbah panas mesin mobil untuk menyalakan peralatan elektronik pada mobil.

Kata-kata kunci: Tekanan rata-rata; Loop radius; Mesin thermoacoustic

1. Introduction

According to the data from the Ministry of Energy and Mineral Resources (ESDM) in the 2019 Indonesia Energy Outlook book (OEI), total energy production in Indonesia tends to decrease in several sectors [1]. Given the depletion of fossil energy in Indonesia and the commitment to reduce greenhouse effect, renewable energy that is more environmentally friendly is needed. The Indonesian Government, through Government Regulation Number 79 of 2014 on the National Energy Policy, has arranged it to overcome this energy crisis. Where the target of the new and renewable energy mix in 2025 is at least 23% and 31% in 2050 [2]. Therefore, there is a need for research on the existence of new energy that is environmentally friendly to support energy production in Indonesia, one of which is energy produced from the thermoacoustic process.

Thermoacoustic is a study of the field of interaction between heat and sound, namely about the conversion of thermal energy into sound energy (acoustic) and vice versa [3]. To produce thermoacoustic effects, thermoacoustic devices are needed [4], namely the thermoacoustic engine (prime mover) [5], [6] and thermoacoustic cooler [7], [8], which is often referred to as the heat pump [9]. Several studies have been conducted to improve the efficiency of the performance of thermoacoustic engines. According to Swift and Back exhaust, the use of looped tubes has greater efficiency than using straight tubes [10]. This is because the looped tube is moved by a traveling wave that performs operations with a reversible stirling cycle compared to a straight tube that is done by a standing wave so that it experiences an irreversible process [11].

There are many applications for the thermoacoustic engines. Swift in 1988 demonstrated a thermoacoustic engine [9]. He was also conducted an investigation about a large thermoacoustic engine. He found that the efficiency of the engine is only 13 % and the heating temperature is 700 °C [12]. In 2002 Yazaki et. al also had an investigation about a thermoacoustic engine. However, They did not calculate the efficiency of the engine [13]. Moreover, in 2016 and 2017 Farikhah et. al did the calculation of the thermoacoustic engine [14], [15]. In 2017 Farikhah et. al investigated the effect of

porosity on the performance of the engine. They found that efficiency is 72% but the heating temperature is 295 °C [16]. They found that the efficiency of the engine achieved 75 %. However, the heating temperature is still high at 523 °C. Likely, in 2020 Farikhah did the numerical calculation and got the results that the efficiency of the engine is 75%. However, the onset heating temperature is 307 °C [8]. Experimental research and numerical studies have been carried out to obtain the lowest onset temperature and highest engine efficiency. According to Zang et al, there are several parameters in order to get the lowest heating temperature and highest engine efficiency, it is mean pressure [12], stack's radius [13], stack's length [14], etc. All of the investigations done by other researchers the heating temperature is still high which is impossible for utilizing waste heat from car engines since the waste heat of the engine car is lower than 200 °C. Therefore, in our study, we want to focus on finding the low onset heating temperature while keeping the efficiency still high.

Based on those problems, this research carried out by examining numerically to determine the lowest onset temperature and highest efficiency by variating the mean pressure and the loop's radius on traveling wave thermoacoustic engine by looped tube.

2. Method

2.1. Calculation Model

The scheme of the thermoacoustic engine system which is the calculation model in this study is shown in **Figure 1**. The thermoacoustic engine used in this study uses a looped tube that is generated by travelling wave. Components in this thermoacoustic machine include: a loop, a hot-heat exchanger, an ambient heat exchanger, and a thermal buffer tube. As a control variable, the length of the circular pipe L_{Loop} set of 2.8 meters, the narrow channel radius of the regenerators r_s 0.7 mm, the length of the loop L_{stack} 7 cm, the porosity of the loop p_s 0 9, and the working gas used is helium with a pressure of 501 KPa.

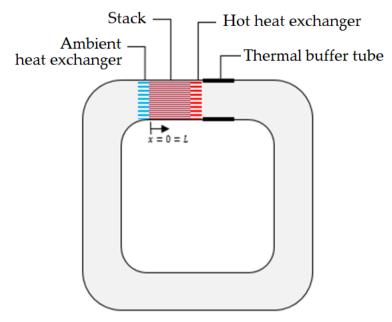The loop's radius is denoted as R_{Loop}. In this calculation, the mean pressure P_m and the radius

Figure 1. Schematic of a thermoacoustic engine system

of the loop R_{Loop} are used as parameters to find the low heating temperature and efficiency of the thermoacoustic engine. The temperatures at the hot-heat exchanger and ambient-heat exchanger are denoted as T_H and T_A, respectively. In numerical calculations, the T_A value is determined according to room temperature, which is $301\ K$ or $28\ °C$. As for T_H, it is determined by calculating the stability limit, where the independent variables are used one by one to get the lowest heating power.

2.2. Calculation Method

In computational calculations, the acoustic approximation equation is used by Rott [15] is used as presented in Eq. (1) and Eq. (2).

Where P shows the oscillation pressure fluctuation, U as the flow velocity fluctuation, ω is the angular frequency of the sound wave, ρ_m is the average density, A is the pipe cross-sectional area, γ is the specific heat ratio, T_m is the average gas temperature, P_m is the mean pressure, and σ is the Prandtl stipulation number. While, ρ_m, γ and σ depends on T_m and x is the coordinate axis along the pipe [16].

When $\frac{dT_m}{dx} = 0$, Eq. (2) can be solved analytically. This is because $\rho_m, \gamma, \chi_a, \chi_v$ and σ are not bound to x, so that the second form on the right side of Eq. (2) is lost. When the oscillator pressure and volume velocity at the point x_0 are notated by P_0 and U_0, the solution can be solved by the Eq. (3).

When $\frac{dT_m}{dx} \neq 0$, the solutions for Eq. (2) will be difficult to solved by analytics, so it have to computationally integrated. The solutions will be solved by fourth-order Runge-Kutta method as presented in Eq. (4).

$$\frac{dP}{dx} = -\frac{1}{A}\frac{i\omega\rho_m}{1 - \chi_\alpha}U \tag{1}$$

$$\frac{dU}{dx} = -\frac{i\omega A[1 + (\gamma - 1)\chi_\alpha]}{\gamma P_m}P + \frac{\chi_\alpha - \chi_v}{(1 - X_v)(1 - \sigma)}\frac{1}{T_m}\frac{dT_m}{d_x}U \tag{2}$$

$$\frac{d}{dx}\begin{pmatrix} P(x,t) \\ U(x,t) \end{pmatrix} = C(x)\begin{pmatrix} P(x,t) \\ U(x,t) \end{pmatrix}, \text{ then}$$

$$C(x) \equiv \begin{pmatrix} 0 & -\frac{1}{A}\frac{i\omega\rho_m}{1 - \chi_v} \\ -\frac{i\omega A[1 + (\gamma - 1)\chi_a]}{\gamma P_m} & \frac{\chi_a - \chi_v}{(1 - \sigma)(1 - \chi_v)}\frac{1}{T_m}\frac{dT_m}{dx} \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} P(x + \Delta x, t) \\ U(x + \Delta x, t) \end{pmatrix} = (E + \Delta x C'(x)) \begin{pmatrix} P(x, t) \\ U(x, t) \end{pmatrix}$$

$$C'(x) = \frac{1}{6}(RK_1 + 2RK_2 + 2RK_3 + RK_4)$$

$$RK_1 = C(x)$$

$$RK_2 = C(x + \Delta x/2)\left(E + \frac{\Delta x}{2}RK_1\right)$$

$$RK_3 = C(x + \Delta x/2)\left(E + \frac{\Delta x}{2}RK_2\right)$$

$$RK_4 = C(x + \Delta x)(E + \Delta x RK_3) \tag{4}$$

Here E is a unit matrix, hence:

$$\begin{pmatrix} P(x, t) \\ U(x, t) \end{pmatrix} = M_{11}(x, x_0) \begin{pmatrix} P_0(x_0, t) \\ U_0(x_0, t) \end{pmatrix} \tag{5}$$

$$M_{11}(x, x_0) \equiv (E + \Delta x C'_{n-1})(E + \Delta x C'_{n-2}) \dots (E + \Delta x C'_1)(E + \Delta x C'_0) \tag{6}$$

Where n is a partition number, which has the meaning of being the separator number between x_0 and x, Δx is defined as $.(x - x_0)/n$, and C'_j shows C' in $x = x_0 + j\Delta x$.
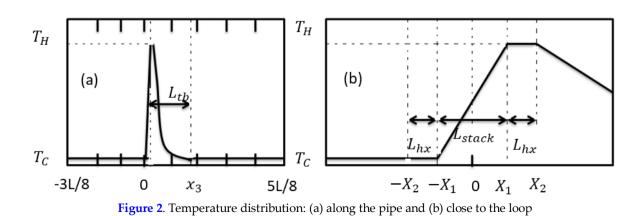
Ueda explained a method for calculating the stability of the oscillation constant limit gas for straight tube and looped tube. This is importance to obtain the onset heating temperature to produced acoustic power. Then the power can be used for the other energy for example for thermoacoustic refrigeration/ Air Conditioner or thermoacoustic electric power generation. On the graph shown in **Figure 2**, the temperature distribution along the pipe is shown and the temperature distribution is close to the loop.

From **Figure 2**, it is known that the transfer matrix T_m is kept constant at $x = -3L/8$ to X_2. The transfer matrix $M_{I,1}$ is calculated using M_1. The ambient-heat exchanger transfer matrix $M_{I,chx}$ is calculate from $x = -X_2 - X_1$, and the hot-heat exchanger transfer matrix $M_{I,hhx}$ which is represented by a range of regions $x = X_1$ up to X_2, and a transfer matrix in the region $x = X_3$ up to $5L/8$ that symbolized $M_{I,2}$.

T_m express constant except in the range of the loop $x = -X_1$ up to X_1 and thermal buffer tube from X_2 up to X_3, which are then denoted in a row with $M_{II,s}$ and $M_{II,tb}$. Equation (6) can be used to calculate the transfer matrix $M_{II,s}$ and $M_{II,tb}$. The partition number is $n = 100$, because it's have been research that the calculation of the stability limit with the partition number n = 100, 200, and 400 shows the same value. Using all available transfer matrices, we can calculate the total matrix system M_{all}:

$$M_{all} = M_{I,2}M_{II,tb}M_{I,hhx}M_{II,s}M_{I,chx}M_{I,1} \tag{7}$$

Figure 2. Temperature distribution: (a) along the pipe and (b) close to the loop

Using all total matrix system M_{all}, the oscillation pressure $P_{E,A}$ and oscillation velocity $U_{E,A}$ have a similar relations in $x = -3L/8$ to the $P_{E,A}$ and $U_{E,A}$ when $x = 5L/8$, so:

$$M_{all}\begin{pmatrix} P_{E,A} \\ U_{E,A} \end{pmatrix} = \begin{pmatrix} P_{E,B} \\ U_{E,B} \end{pmatrix} \tag{8}$$

In looped tube, there is a slight difference in calculating the stability of the limit. When the $P_{E,A}$ and $U_{E,A}$ at $x = -3L/8$ same with position at $x = 5L/8$. Thus, Eq. (8) can be expressed by:

$$M_{all}\begin{pmatrix} P_{E,A} \\ U_{E,A} \end{pmatrix} = \begin{pmatrix} P_{E,A} \\ U_{E,A} \end{pmatrix} \tag{9}$$

The solution for $(P_{E,A}, U_{E,A})$ will not be zero if the determinant of the matrix $(M_{all} - E)$ is zero, or can be specified as:

$$(m_{11} - 1)(m_{22} - 1) - m_{12}m_{21} = 0 \tag{10}$$

Here E denotes the unit matrix of m_{ij} which is the element of M_{all}. Thus, Eq. (10) can determine the stability limit conditions of the spontaneous gas oscillation induced in the looped tube thermoacoustic engine [17]. Then, we can find the onset heating temperature.

In understanding thermoacoustic devices, we need to describe the power that connected with thermoacoustic wave propagation [18]. This is because an acoustic wave causes pressure, density, and temperature changes in a thermoacoustic device, which is very necessary for energy conversion between heat and work [19]. In his study, Rott formulated:

$$H = \dot{W} - \dot{Q} \tag{11}$$

As a mathematical calculation, we need to calculate the acoustic power equation $\dot{W}[W]$, acoustic heat power $\dot{Q}$ [W] [18] which is indicated by oscillation pressure P and the average of cross-sectional area A of the oscillation velocity U. The equation becomes [20]:

$$\dot{W} = IA = \frac{1}{2}Re[P\tilde{U}] \tag{12}$$

$$\dot{Q} = \frac{1}{2}ARe\left[P\tilde{U}\left(\frac{\widetilde{\chi_v} - \chi_\propto}{(1+\sigma)(1-\chi_v)}\right)\right]$$
$$- A\frac{\rho_m c_p |U|^2}{2\omega(1-\sigma^2)|1-\chi_v|^2}Im(\chi_\alpha$$
$$+ \sigma\tilde{\chi}_v)\frac{dT_m}{dx} \tag{13}$$

Equation (12) and Eq. (13) can be substituted into Eq. (11) to become Eq. (14).

$$\frac{dTm}{dx} = \frac{\dot{H} - \frac{A}{2}Re\left[P\tilde{U}\left(1 - \frac{\widetilde{\chi_v} - \chi_\propto}{(1+\sigma)(1-\chi_v)}\right)\right]}{A\frac{\rho_m c_p |U|^2}{2\omega(1-\sigma^2)|1-\chi_v|^2}Im[\chi_\alpha + \sigma\tilde{\chi}_v]} \tag{14}$$

In his paper, Yazaki explained that when the onset heating temperature T_H exceeds the critical temperature, the gas will be spontaneous oscillating [21]. This means, acoustic waves will pass through a circular tube and transfer energy spontaneously. In this case, the acoustic power generated from the spontaneous oscillation $\Delta\dot{W}_{E,A}$ is an input for the ambient-heat exchanger and the power booster in the loop's machine. In addition, acoustic power $\Delta\dot{W}_{E,A}$ can be generated from the number of loop engine heat exchangers [22]. So, the additional acoustic power on the engine loop can be formulated into:

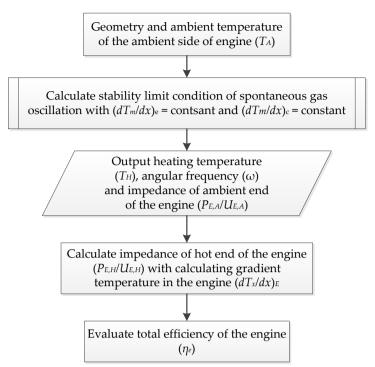$$\Delta\dot{W}_E = \dot{W}_{E,H} - \dot{W}_{E,A} \tag{15}$$

Furthermore, to increase acoustic power, the hot-heat exchanger needs to supply acoustic thermal power $\dot{Q}_H$. Thus, the efficiency of the engine loop can be written in the equation:

$$\eta_{E1} = \frac{\Delta\dot{W}_e}{\dot{Q}_H} \tag{16}$$

In this study, we used the efficiency that depend by onset heating temperature. The equation is written bellow [22]:

$$\eta_{E2} = \frac{\eta_e}{\eta_{carnot}} \tag{17}$$

Overall, the calculations for the total engine efficiency are presented in **Figure 3**.

Figure 3. Flow chart for evaluating efficiency of the engine (η_e)

3. Resuts and Discussion

The results of this study are presented in the graphs relations of T_H and η_{E2} for variations in mean pressure and loop's radius in **Figure 4** and **Figure 5**.

Figure 4 shows the lowest onset temperature T_H has decreased dramatically starting from mean pressure P_m of 0.5 MPa - 2 MPa, and tends to decrease constantly from 2 - 4 MPa. When R_{Loop} got increased, the T_H shows gradually decreasing. From this graph it can be seen that the lowest onset temperature is obtained in 153 °C when P_m is 4.0 MPa and R_{Loop} is 5 cm. T_H is influenced by the phase of the wave ϕ. This can be observed by **Figure 6**.

According to **Figure 6**, when R_{Loop} = 5 cm and P_m = 4.0 Mpa, the lowest phase ϕ is generated at 50,7°. This is the same as the graph in **Figure 4**, which also T_H reaches the lowest value in that position. This phase is inversely proportional to the acoustic power produced. The lowest ϕ, will produce the highest acoustic power ΔW. This is in accordance with the equation by Ueda [11]:
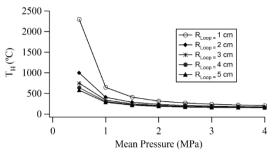
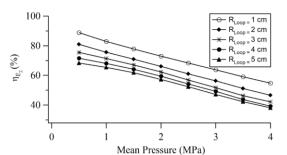$$\frac{\Delta W}{\dot{W}} \cong \frac{\Delta P}{P} + \frac{\Delta U}{U} - tan\phi.\Delta\phi \qquad (16)$$

In **Figure 5**, the efficiency decreases linearly as the decreases of P_m. On the graph it can be observed, efficiency also decreases as the loop's radius R_{Loop} decreases. From the graph, it can be seen that the highest efficiency is obtained when P_m is 0.5 MPa and R_{Loop} 1 cm, which is equal to 88.8%.

Figure 4 and **Figure 5** show that to achieve high efficiency, high onset temperatures are also needed. When P_m is 0.5 MPa and R_{Loop} 1 cm, the highest efficiency is obtained, but the required onset temperature is also high, reaching 2295 °C. Conversely, when the P_m is 4 MPa and R_{Loop} 5 cm, the lowest heating temperature is obtained in 153 °C, but the resulting efficiency is not too large, only 38.1%. Select the proper parameters is needed to get the highest efficiency or to get the lowest onset temperature. In this research, the most properest to execute is at P_m of 2 MPa and R_{Loop} 5 cm. This election is not solely without reason because is produce T_H 174 °C wich including in low grade waste heat [23] the most generated from industrial activity [24].
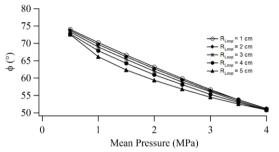
In the calculation η_{E2}, the actual efficiency of a machine η_{E1} is compared with the carnot efficiency η_C according to the Eq. (15). The higher the actual efficiency value and the lower the carnot efficiency value, it will reach its maximum η_{E2}. The relation of η_{E1}, η_C and P_m are shown in **Figure 7** and **Figure 8**, it can be seen both of η_{E1} and η_C reach their maximum values when they are used P_m 0.5 MPa and R_{Loop} 1 cm. This is evidence of involvement η_{E1} and η_C to η_{E2}.
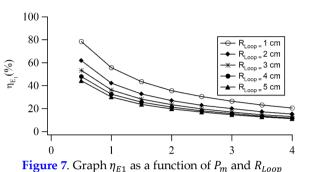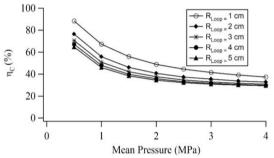
Figure 4. Graph T_H as a function of P_m and R_{Loop}

Figure 5. Graph η_{E2} as a function of P_m and R_{Loop}

Figure 6. Graph of ϕ as functions of P_m and R_{Loop}

Figure 7. Graph η_{E1} as a function of P_m and R_{Loop}

Figure 8. Graph η_C as a function P_m and R_{Loop}

4. Conclusion

In this study, the lowest onset temperature is T_H 153 °C which is more affordable for waste heat in the engine car to be converted to another useful energy. This temperature is obtained when the mean pressure P_m 4 MPa is used and the radius of the loop is 5 cm. With this onset temperature, the efficiency of the engine produced is 38 %. In this study, it can be concluded that there is an effect of mean pressure and loop's radius on the of onset heating temperature and thermoacoustic engine efficiency. The engine model gives guidance for researchers who work experimentally to select parameter for getting low heating temperature.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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