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Numerical analysis on a four-stage looped thermoacoustic Stirling power generator for low temperature waste heat

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Abstract

Recent developments in thermoacoustic technologies have demonstrated that multi-stage looped thermoacoustic Stirling engine would be a promising option for harvesting waste heat. Previous studies on multi-stage looped thermoacoustic systems were mainly focused on heat-driven refrigeration or heat pumping, while much fewer work were done on power generations, especially those for recovering low temperature heat. In this work, a four-stage looped thermoacoustic Stirling power generator for generating electricity from low temperature waste heat at 300 °C is systematically studied. A numerical model is built and then validated on an experimental four-stage looped thermoacoustic Stirling engine. On the basis of the validated model, the effects of the coupling position for the linear alternators and the regenerator position on the acoustic characteristics and performances of the power generation system are numerically investigated. The distributions of the acoustic fields along the loop, including the pressure amplitude, volume flow rate, phase angle, specific acoustic impedance and acoustic power, are presented and analysed for three representative coupling modes. Superior efficiency is achieved when the linear alternators are coupled near the cold ends of the thermoacoustic cores on the resonators, while more electric power is generated at the hot ends. The worst performance is expected when the linear alternators are connected at the middle of the resonators. The underling mechanisms are further explained detailedly by analysing the characteristics of the acoustic fields and output acoustic impedances for different coupling modes. Furthermore, the regenerator position in the thermoacoustic cores is found to have a remarkable influence on the output electric power, while it is less important for the efficiency. The optimized four-stage looped thermoacoustic Stirling power generator is able to provide a maximum electric power of 1223 W with a highest relative Carnot efficiency of around 0.20. This work provides in-depth insights into the operation principle of the looped thermoacoustic Stirling power generator and will be helpful for future developments of similar waste heat recovery systems.

Keywords: looped thermoacoustic engine; multi-stage; power generator; waste heat; Stirling engine; acoustic field

Nomenclature

A	Cross-sectional area of gas channel, m^2	R_m	Mechanical resistance, $\text{N}\cdot\text{s}/\text{m}$
A_p	Piston area, m^2	T_a	Ambient temperature, K
A_s	Cross-sectional area of solid, m^2	T_h	Heating temperature, K
Bl	Force factor, N/A	T_m	Mean temperature, K
c	Sound speed, m/s	U_1	Volume flow rate, m^3/s
c_p	Specific heat, $\text{J}/(\text{kg}\cdot\text{K})$	v_1	Piston velocity, m/s
C_e	Electric capacitance, F	V_b	Back volume, m^3
f	Frequency, Hz	W_{ac}	Acoustic power extracted by load, W
f_K	Spatial averaged thermal function	W_e	Electric power, W
f_V	Spatial averaged viscous function	W_{loop}	Acoustic power in the loop, W
H	Total energy flow, W	x	Coordinate, m
I_1	Electric current, A	z	Specific acoustic impedance, $\text{Pa}\cdot\text{s}/\text{m}$
j	$\sqrt{-1}$	Z	Acoustic impedance, $\text{Pa}\cdot\text{s}/\text{m}^3$
k	Thermal conductivity of gas, $\text{W}/(\text{m}\cdot\text{K})$	γ	Specific heat ratio
k_s	Thermal conductivity of solid, $\text{W}/(\text{m}\cdot\text{K})$	η_{ac}	Relative Carnot efficiency of acoustic power
K	Mechanical stiffness, N/m	η_e	Relative Carnot efficiency of electric power
L_e	Winding inductance, H	θ	Phase difference, rad
M	Moving mass, kg	ρ_m	Mean density, kg/m^3
p_1	Pressure amplitude, Pa	ω	Angular frequency, rad/s
p_m	Mean pressure, Pa	$/ /$	Magnitude of a complex value
Pr	Prandtl number	$\text{Im}[]$	Imaginary part of a complex value
Q_h	Heating power, W	$\text{Re}[]$	Real part of a complex value
r_e	Winding resistance, Ω	$\sim$	Complex conjugate
R_e	Load electric resistance, Ω		

1 Introduction

Technologies for power generation from waste heat have drawn increasing attention in the past years. Recent developments on thermoacoustic systems showed that thermoacoustic Stirling engines would be one of the

promising alternatives for waste heat recovery, thanks to their unique features of low-temperature operation capability, simple structure, high reliability and low costs [1, 2].

The first thermoacoustic Stirling engine was in a looped shape with a uniform diameter, built by Yazaki [3]. However, the efficiency was poor because of the low impedance and high viscous loss in the regenerator. Extensive later work were based on the type of thermoacoustic Stirling engine proposed by Backhaus and Swift [4], in which a standing-wave resonator was connected to a short loop for enhancing the regenerator impedance. The Backhaus-Swift type thermoacoustic engine has much lower losses in the regenerator, and is able to work efficiently at a relatively high driving temperature (~ 650 °C), with a typical output thermal efficiency of around 20%-30%. The studies on thermoacoustic Stirling engines were focused on improving output performances [5-7], increasing working frequency [8-10], lowering operating temperature [11-12], driving cryocoolers/thermoacoustic coolers for refrigeration [13-15], exploring onset mechanisms [16-18], and so on. Many efforts were recently devoted into employing the engine for power generation by using linear alternators [19-25]. However, it is challenge for those machines to operate efficiently at a low driving temperature, such as temperatures around or less than 300 °C, mainly because of the lossy standing-wave resonator. In 2010, de Blok proposed a multi-stage looped thermoacoustic Stirling engine [26,27]. Multiple regenerators were symmetrically placed in a one-wavelength resonator. The acoustic field in the resonator was near a traveling wave, having lower losses for transferring acoustic power compared to a standing-wave resonator used in a Backhaus-Swift engine. The multi-stage amplification of the acoustic power through the multiple regenerators enhanced the power amplification effect. The cross-sectional areas of the regenerators were much larger than the resonator, which largely reduced the flow velocity and the associated viscous losses. The operation temperature of the prototype system was therefore much lower than those of traditional ones, i.e. only 100 °C, whereas considerably high efficiency was still achievable. This new concept makes looped thermoacoustic engines more cost-effective and attractive for waste heat recoveries. Great attention has been drawn into looped thermoacoustic engines thereafter [28-37]. The onset characteristics, acoustic fields and performances of looped thermoacoustic engines have been investigated numerically and experimentally by many researchers [26, 31-33]. As a heat-driven prime mover, looped thermoacoustic engines can be used for refrigeration and power generation. Zhang et al. [34] and Jin et al. [35] analysed the operation features of looped thermoacoustic engine driven refrigerators for utilizing low grade thermal energy. Xu et al. [36] built a three-stage looped thermoacoustically-driven cryocooler for liquefying natural gas. In the aspect of power generation, however,

much less work has been conducted. A latest experimental work was reported by Bi et al. [37] on a three-stage looped thermoacoustic power generator operating at a relatively high temperature, i.e. 650 °C.

Up to now, few studies on multi-stage looped thermoacoustic Stirling power generators are available, especially those for recovering low temperature heat. Previous work on thermoacoustic-linear alternator coupled systems showed that the acoustic matching between them is critical for the overall performance [19]. However, none studies have been focused on the coupling characteristics and the operation features on a multi-stage looped thermoacoustic Stirling power generator. Therefore, the current work aims to explore the effects of coupling mode on the acoustic fields and energy conversions in a four-stage looped thermoacoustic Stirling power generator targeting for recovering low temperature waste heat. In addition, the effect of the regenerator position on the performance will be further analysed.

2 System configuration

Figure 1 illustrates the four-stage looped thermoacoustic Stirling power generator, which is composed of four thermoacoustic cores and four linear alternators distributed uniformly on four quarter-wavelength resonators. The parameters of the linear alternators are selected based on a commercial product [38], as listed in Table 1. The thermoacoustic core consists of a compliance tube, two ambient heat exchangers, a regenerator, a hot heat exchanger and a thermal buffer tube. The main dimensions are listed in Table 2. The operating frequency of the system is dominated by the void volume in the thermoacoustic cores and the length of the resonators. The designed frequency is near 70 Hz with helium at 3.0 MPa as the working gas. Three coupling modes between the thermoacoustic engine and the linear alternators, namely cold-end coupling, middle coupling, and hot-end coupling, are denoted by different types of arrows. The linear alternators are placed in the middle coupling position in Figure 1.

Figure 1. Schematic of the four-stage looped thermoacoustic Stirling power generator.

Table 1. Main parameters of the linear alternators.

Parameter	Value
Force factor Bl (N/A)	46
Winding inductance L_e (mH)	46
Winding resistance r_e (Ω)	2
Mechanical stiffness K (kN/m)	46
Mechanical resistance R_m (Ns/m)	7
Moving mass M (kg)	0.721
Piston area A_p (cm^2)	18.331
Back volume V_b (cc)	450

Table 2. Main geometric dimensions of the four-stage thermoacoustic Stirling power generator.

Component	Diameter (mm)	Length (mm)	Porosity
Compliance tube	100	100	1
Ambient heat exchanger	100	30	0.25
Regenerator	100	20	0.7
Hot heat exchanger	100	40	0.5
Thermal buffer tube	100	100	1
Secondary ambient heat exchanger	100	30	0.25
Resonator	25	2.25	1

3 Model description and validation

Numerical simulations are based on the linear thermoacoustic theory, and implemented in DeltaEC software [39] which is widely used for thermoacoustic studies [21,34,35]. Each component of the practical system is represented by a corresponding module and linked logically in the model. The parameters, including pressure, volume flow velocity, temperature, energy flow and frequency, are numerically calculated by a guess-target shooting method after setting the boundaries.

The frequency-domain momentum, continuity and energy equations of various components and flow channels in a thermoacoustic engine are expressed as follows [39],

$$\frac{dp_1}{dx} = -\frac{j\omega\rho_m U_1}{(1-f_v)A} \quad (1)$$

$$\frac{dU_1}{dx} = -\frac{j\omega A}{\gamma p_m} \left[1 + (\gamma - 1)f_\kappa \right] p_1 + \frac{(f_\kappa - f_v)U_1 dT_m}{(1-f_v)(1-\text{Pr})T_m dx} \quad (2)$$

$$\frac{dT_m}{dx} = \frac{H - 0.5\text{Re} \left[p_1 \tilde{U}_1 \left(1 - \frac{f_\kappa - \tilde{f}_v}{(1-\tilde{f}_v)(1+\text{Pr})} \right) \right]}{\frac{\rho_m c_p |U_1|^2}{2A\omega(1-\text{Pr}^2)|1-f_v|^2} \text{Im} [f_\kappa + \text{Pr} \tilde{f}_v] - (Ak + A_s k_s)} \quad (3)$$

where p_1 , U_1 , T_m and H are complex pressure amplitude, complex volume flow rate amplitude, mean temperature of working gas, and total energy flow, respectively; f_κ and f_v denote thermal and viscous functions; k and k_s are thermal conductivities of gas and solid; ω , γ , Pr , c_p and p_m represent angular frequency, specific heat ratio, Prandtl number, heat capacity and mean pressure, respectively; A , A_s and x are cross-sectional area for gas flow, solid cross-sectional area and coordinate along sound-propagation direction.

The governing equations of the linear alternator is given by,

$$Bl \cdot v_1 = I_1 \left(R_e + r_e + j\omega L_e - j \frac{1}{\omega C_e} \right) \quad (4)$$

$$p_1 A_p = Bl \cdot I_1 + R_m v_1 + j\omega M v_1 - j \left(\frac{K}{\omega} v_1 + \frac{\gamma p_m v_1 A_p^2}{\omega V_b} \right) \quad (5)$$

where v_1 and I_1 are amplitudes of velocity and current, respectively.

The acoustic impedance Z is defined by,

$$Z = \frac{p_1}{U_1} = \text{Re} \left[\frac{p_1}{U_1} \right] + j \text{Im} \left[\frac{p_1}{U_1} \right] \quad (6)$$

The total output acoustic power delivered to the four linear alternators from the four-stage looped thermoacoustic engine, W_{ac} , is defined as,

$$W_{ac} = \sum_4 \frac{1}{2} |p_1| |U_1| \cos \theta \quad (7)$$

where θ is the phase difference between pressure amplitude and volume flow rate.

The total electric power generated by the linear alternators, W_e , is calculated as,

$$W_e = \sum_4 \frac{1}{2} |I_1|^2 R_e \quad (8)$$

where I_1 and R_e are the electric current and the load electric resistance for each linear alternator.

The relative Carnot efficiency of the output acoustic power, η_{ac} , is defined by,

$$\eta_{ac} = \frac{W_{ac}}{Q_h \left(1 - \frac{T_a}{T_h} \right)} \quad (9)$$

where Q_h is the total heating power applied to the engine; T_a and T_h denote the ambient and heating temperatures, respectively.

Similarly, the relative Carnot efficiency of the electric power, η_e , is calculated by,

$$\eta_e = \frac{W_e}{Q_h \left(1 - \frac{T_a}{T_h} \right)} \quad (10)$$

The low-temperature four-stage looped thermoacoustic engine developed by de Blok [26,40] has been used for validating the model. The system was pressurized with helium gas, operated at a frequency of about 90 Hz. The simulated frequency is near 91 Hz, which is close to the measurement result. Figure 2 illustrates the measured and simulated acoustic powers in the loop at three working pressures. The results show reasonable agreements between the simulations and the experiments in both trends and magnitudes. Most of the deviations are within 10%. For the mean pressure of 3.1 MPa, the averaged deviation is 7.7%. When the temperature difference is 90

K at 2.1 MPa, the pressure amplitudes near the thermoacoustic core are 52.5 kPa and 57.2 kPa for the experiment and simulation respectively, showing that the model is able to predict the performances well.

Figure 2. Experimental and simulated acoustic powers in the loop of the four-stage looped thermoacoustic Stirling engine.

4 Results and discussion

The four-stage looped thermoacoustic Stirling power generator is designed for recovering low temperature heat. Helium gas at 3.0 MPa is used as the working fluid. In the simulations, the hot heat exchangers are set at 573 K, and the ambient heat exchangers are fixed at 300 K. The heating temperature is widely available from various industrial processes, such as exhausts from steam boiler, gas turbine, reciprocating engine, ovens, etc. The length of the regenerators is selected as 20 mm, resulting in a temperature gradient of 13.65 K/mm. This temperature gradient is a little higher than the one in Ref. [4] (about 9.60 K/mm), which was targeting for a high operating temperature (>700 °C). This ensures that the driving temperature gradient is powerful enough for acoustic power amplification while keeping the thermal conduction loss in a low level. Each of the four linear alternators is connected with a variable load resistance. Electric capacitances of 50 μ F are connected in the circuits to offset the winding inductances for a better acoustoelectric efficiency. In order to have a uniform distribution of acoustic field, the four load resistances are always kept the same in the adjustment. In practical engines, the acoustic streaming around the loop can be blocked by using an elastic membrane. Therefore, the acoustic streaming is not necessarily considered in the model. For simplicity, the loss caused by the membrane is ignored. In the following sections, the impacts of coupling mode and regenerator position on the power generation system will be presented and analysed.

4.1 Effect of coupling mode

Figure 3 illustrates the frequency dependency on the load resistance for the three coupling modes. The cold-end coupling mode shows the highest frequency, followed by the hot-end coupling mode, and the middle coupling mode has the lowest frequency. In general, the differences are small. The acoustic impedances of the linear alternator at the three coupling modes are shown in Figure 4. It indicates that the real part of the linear alternator is highly dependent on the load resistance. It decreases significantly with the load resistance. No obvious differences between the real parts are observed for the three coupling modes. Larger differences exist for the imaginary part, especially at a high load resistance.

Figure 3. Frequency f of the four-stage looped thermoacoustic Stirling power generator with different coupling modes.

Figure 4. Acoustic impedance Z of the linear alternator with different coupling modes.

The distributions of the acoustic fields in the four-stage looped thermoacoustic Stirling power generator with different coupling modes at the load resistance of 50 Ω are presented in Figure 5. As shown, all the acoustic

parameters show periodical variation trends in the four stages. Remarkable differences in the acoustic fields exist for the three coupling modes. The middle coupling mode has the highest pressure amplitude and volume flow rate, as shown in Figures 5(a) and (b). According to the distributions of pressure and volume flow rate along the loop, the pressure amplitude is the lowest while the volume flow rate is the highest at the middle of the resonator. It indicates that the middle coupling position is a low acoustic impedance region, which also requires a low load acoustic impedance for better output performances [19]. Compared with the middle coupling mode, the hot-end coupling mode shows lower values in pressure and volume flow rate amplitudes along the majority part of the loop, and the cold-end coupling mode generates the lowest oscillations. Since the pressure amplitude is much higher at the two ends of the resonator than that at the middle position, the local acoustic impedances at the positions for the hot-end and cold-end coupling modes are both higher than that for the middle one. Figure 5(c) is the distribution of the phase angle between pressure and volume flow. It shows that the phase angle goes across the zero phase in the thermoacoustic cores for all the three coupling modes. The phase angle along the resonator in the multi-stage looped thermoacoustic engine is much closer to zero than that in a Backhaus-Swift type thermoacoustic Stirling engine, where it is typically near 90° . The near-zero phase angle enables the looped thermoacoustic engine to transfer more acoustic powers through the resonator without too much dissipation. As shown in Figure 5(c), the phase angle along the resonator is the closest to zero at the cold-end coupling mode, followed by the hot-end coupling mode, and the middle coupling mode has the worst phase angle. The discontinuities for the volume flow and the phase angle are contributed by the linear alternators. Figure 5(d) shows that the looped thermoacoustic power generator has large specific acoustic impedances in the thermoacoustic cores. The specific acoustic impedance is all about 10 in the regenerators for the three coupling modes. It indicates that the enlarged cross-sectional area in the thermoacoustic cores reduces the flow velocity effectively, which is critical for an efficient operation. No significant difference in specific acoustic impedance exists for the three coupling modes. The acoustic power distribution along the thermoacoustic power generator is given by Figure 5(e). It shows that the acoustic power flowing round the loop is at the lowest level for the cold-end coupling mode, while those in the hot-end and middle coupling modes are much higher. This is because the intensity of the acoustic oscillation in the cold-end coupling mode is not as strong as those in the other two modes, as shown in Figures 5(a) and (b).

Figure 5. Distributions of acoustic parameters along the axial direction x of the four-stage looped thermoacoustic Stirling power generator with different coupling modes. (a) pressure amplitude $|p_1|$, (b) volume flow rate amplitude $|U_1|$, (c) phase angle θ , (d) specific acoustic impedance $|z|/(\rho_m c)$, (e) acoustic power W_{loop} in the loop.

Figure 6 shows the output electric power and the corresponding relative Carnot efficiency for the three coupling modes. As shown, the system with the middle coupling mode shows the worst performance among the three modes. The reason for the low electric power is due to the low driving pressure at the middle of the resonator, as shown in Figure 5(a). In the meanwhile, however, the pressure oscillation intensity is the strongest along the loop compared to those of the other two modes, leading to the highest acoustic power dissipation rate and the lowest efficiency. For the cold-end and hot-end coupling modes, the performances are much better. The system with the cold-end coupling mode obtains the highest relative Carnot efficiency. The maximum relative Carnot

efficiency reaches 0.20 with an output electric power of 975 W at 37.5 Ω . The maximum electric power for the cold-end coupling mode reaches 1047 W with an efficiency of 0.171 at 65.5 Ω . It indicates that the relatively low pressure oscillation intensity along the system is essentially beneficial for the efficiency because of the low dissipations. The efficiency of the hot-end coupling mode is in-between the ones of the other two modes. However, the hot-end coupling mode generates the highest electric power, due to the highest driving pressure among the three modes. Compared to the cold-end coupling mode, the hot-end coupling mode has stronger acoustic oscillations along the system, resulting in lower efficiencies. At the most powerful operating point, the system with the hot-end coupling mode is able to deliver an electric power of 1223 W at 44 Ω . The corresponding relative Carnot efficiency is 0.156.

Figure 6. Electric power W_e and relative Carnot efficiency η_e of the four-stage looped thermoacoustic Stirling power generator with different coupling modes.

The different behaviours of the electric power and relative Carnot efficiency for the three modes can also be explained in the perspective of the impedance characteristics of the looped engine. Figure 7 shows the output performances of the four-stage looped thermoacoustic engine for different load acoustic impedances. When the load resistance is 60 Ω , the real parts of the acoustic impedances for the linear alternators are close to 12.9 MPa·s/m³, as shown previously in Figure 4. When the real part of the load acoustic impedance is fixed at 12.9 MPa·s/m³, the dependences of the output acoustic power and the corresponding relative Carnot efficiency on the imaginary part of the load acoustic impedance are given in Figure 7(a). The result indicates that the output characteristics of the engine at the three coupling positions are very different. The optimal acoustic impedance for the middle coupling mode is the smallest, followed by the hot-end and cold-end coupling modes. This is consistent with the previous analyses on the distributions of the pressure and volume flow amplitudes in Figures 5(a) and (b). Following the imaginary impedances in Figure 4, the output acoustic power extracted by the linear

alternators and the corresponding efficiency at $60\ \Omega$ are highlighted by the points in Figure 7(a). Apparently, similar to the trends of electric power in Figure 6 for $60\ \Omega$, the extracted acoustic power is the largest for the hot-end coupling mode, and smallest for the middle coupling mode. Similar to the efficiency in Figure 6, the efficiency of the extracted acoustic power is superior at the cold-end coupling mode according to Figure 7. For the load resistance of $20\ \Omega$, the output characteristics of the engine are shown in Figure 7(b). It indicates that the acoustic powers extracted by the linear alternators for the cold-end and hot-end coupling modes are similar, while the one for middle coupling mode is the lowest. Since the acoustoelectric conversion efficiency of the linear alternators stays almost constantly at 80%, the generated electric powers by the three modes thus show similar relations, as shown in Figure 6.

Figure 7. Output acoustic power W_{ac} and relative Carnot efficiency η_{ac} of the four-stage looped thermoacoustic Stirling engine with different coupling modes at (a) load impedance of $\text{Re}[Z]=12.9\ \text{MPa}\cdot\text{s}/\text{m}^3$ when $R_e=60\ \Omega$, (b) load impedance of $\text{Re}[Z]=28.7\ \text{MPa}\cdot\text{s}/\text{m}^3$ when $R_e=20\ \Omega$.

4.2 Effect of regenerator position

The regenerator position in the thermoacoustic core affects the phase angle of the regenerator, which further influences the overall performances of the system. In this section, the effect of the regenerator position is investigated on the cold-end coupling mode. The regenerator position is adjusted by changing the length of the compliance tube. The length of the thermal buffer tube, which is at the other side of the regenerator, is adjusted accordingly so as to keep the total length of the loop as a constant.

Figure 8 shows the electric power and the corresponding relative Carnot efficiency at different lengths of the compliance tube. It indicates that the electric power increases when decreasing the length of the compliance tube.

The efficiency is less sensitive to the regenerator position, except when the load resistance is relatively high, as shown in Figure 8(b). According to Figure 8(c), the optimal length for the efficiency is 0.13 m, although the differences between the maximum efficiencies at different lengths are very small. It also indicates that the length of the compliance tube, i.e. the regenerator position, should be selected based on the targeting electric power in the design so as to have a good efficiency. For example, when the targeting electric power is 1000 W, the length of the compliance tube should be selected as 0.10 m, since it is able to reach a higher efficiency compared to the length of 0.07 m. The effects of the regenerator position on the frequency and the driving pressure amplitude are shown in Figure 9. It shows that both of them increases as the length of compliance tube decreases.

Figure 8. Electric power W_e and relative Carnot efficiency η_e of the four-stage looped thermoacoustic Stirling power generator with different regenerator positions. (a) Electric power W_e versus load resistance R_e , (b) relative Carnot efficiency η_e versus load resistance R_e , (c) Relative Carnot efficiency η_e versus electric power W_e .

Figure 9. (a) Frequency f and (b) driving pressure amplitude $|p_1|$ of the four-stage looped thermoacoustic Stirling power generator with different regenerator positions.

increased frequency and the pressure amplitudes therefore lead to the higher electric power at a short compliance tube (see Figure 8).

The phase angles at the cold and hot ends of the regenerators are illustrated in Figure 10. As shown, the phase angles at both ends decreases toward negative values when decreasing the length of the compliance tube. This is reasonable according to the distribution of phase angle along the system in Figure 5(c) when the regenerator is moved towards the left direction. When the efficiency reaches 0.204 at the length of 0.15 m (see Figure 8(b)), the corresponding phase angles are -5.86° and 3.71° . However, a comparable efficiency, i.e. 0.206, is still achievable with the phase angles of -11.59° and -2.37° at the compliance tube length of 0.13 m. When the compliance tube length is decreased to 0.10 m, the efficiency is still at a similar level, i.e. 0.202, even though the phase angles have changed to -20.38° and -12.05° . It indicates that the deviated phase angle caused by changing the regenerator position is not a significant factor for the output efficiency of the power generator.

Figure 10. Phase angle θ at the cold and hot ends of regenerator in the four-stage looped thermoacoustic Stirling power generator with different regenerator positions.

5 Conclusions

This work presents numerical simulations on a four-stage looped thermoacoustic Stirling power generator for recovering low temperature waste heat. Numerical model is built by using DeltaEC software and validated on an experimental four-stage looped thermoacoustic engine. Commercial linear alternators are used for converting the generated acoustic power into electric power. The effects of the coupling mode and the regenerator position on the acoustic field and performance of the thermoacoustic power generator are investigated. The following conclusions can be drawn from the results:

(1) The coupling mode (cold-end, middle and hot-end coupling modes) has great effects on the acoustic field distribution and performance. The middle coupling mode shows the worst performance in terms of both electric power and efficiency, due to the large acoustic power dissipation induced by the strong acoustic oscillation. The system with the hot-end coupling mode generates the highest electric power of 1223 W among the three modes, and has improved efficiencies over the middle coupling mode because of the less intensive acoustic oscillation and the better phase angle relations. The cold-end coupling mode reaches the highest relative Carnot efficiency of 0.20 with moderate output electric powers.

(2) The optimal acoustic impedance of the linear alternator required by the looped thermoacoustic engine is highly related to the local acoustic impedance at the coupling position. Since the local acoustic impedance is the lowest at the middle coupling position, the optimal acoustic impedance for this mode is the smallest. The cold-end coupling position locates in a high acoustic impedance region, and thus requires the highest acoustic impedance for the linear alternator. The required acoustic impedance for the linear alternator for the hot-end coupling mode is in-between the above two.

(3) The influence of the regenerator position in the thermoacoustic core on the output electric power is remarkable, while its effect on the efficiency is minor. It is beneficial for the output electric power when the regenerator is moved towards the direction of the ambient heat exchanger. The deviated phase angle caused by changing the regenerator position is not a significant factor for the output efficiency of the system.

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