International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

Vol. 39 No. 1 June 2023, pp. 177-183

Minor Losses Of Cone Segments Insertion Into Single Loop Thermoacoustic Engine Model

Nurpatria[1], Agus Dwi Catur[2]

Department of Mechanical Engineering, Faculty of Engineering, Mataram University

Mataram, Indonesia.

[1]nurpatria@unram.ac.id

[2]agus.dc@unram.ac.id

Abstract – A thermoacoustic engine model has been built with Delta-EC simulation. This engine model is designed with a specific capability to utilize heat source from flue gas of low-grade biomass combustion. This engine model considered has a promising feature for low cost implementation according to the fact that the low-grade biomass abundantly available at rural area in the form of agricultural waste. This engine model is an improved version of a previous one, with the addition of two conical segments in two location at the engine's loop. The cone segments lower the energy loss which in turn improve the overall performance of the engine, compared to the model installed with the straight segments. On a certain setting of the engine's model parameters, their addition be able to slightly decreasing the acoustic energy loss occurred at loop ends and both cold and hot heat exchangers interface. The cone segments increase the engine performance by reducing the acoustic energy loss of 0.2 W, which is 0,3% lower than those with straight segment. In general, overall heat to acoustic conversion efficiency of the model is slightly increase from 6.97% to 7.01%.

Keywords – themoacoustic engine; simulation; acoustic energy loss; cone segment; biomass

I. INTRODUCTION

Global climate change is one of the current challenges for humanity, so awareness has arisen to start reducing the use of fossil fuels which are still the main foundation for global energy fulfillment, reaching 81% according to the World Bioenergy Association [1]. The use of these fossil fuels is considered to be the largest contributor to greenhouse gas emissions, which are the main driver of climate change. Because of this, the use of fossil fuels has begun to be replaced by renewable energy source such as biomass. Apart from being a household fuel, biomass can also be used as a fuel for internal combustion engines and external combustion engines. Moreover, biomass needs to be purified first to become a high grade fuel type so that it can be used in internal combustion engines. Avalailability of technology needed for processing biomass to become high grade fuel type for small scale, for example for household needs in rural areas, is still limited. This limitation is mainly due to the needs of supporting equipment in the process which is still quite complex, and initial installation costs still relatively expensive [1]. These two factors are among restrictions the use of biomass fuel for internal combustion engines. Therefore, biomass as a fuel is more common introduced in the field of external combustion engine applications.

On the other hand, In the last few decades the thermoacoustic engine technology has emerged. This engine is a type of external combustion engine, but it has no moving parts. The engine consists of several main components which all placed in the main channel which forms a loop. It can also be designed to utilize heat sources from various kinds, including the heat from untreatment biomass combustion that categorized as low grade energy source. The heat energy from low grade energy source is then converted into acoustic energy in a thermoacoustic engine component of a porous material knowns as regenerator. Acoustic energy generated by the thermoacoustic engine can be further converted into mechanical energy, in the way of extracting the pressure amplitude from the acoustic waves [2].

The first know succesful basic setup of a single looped thermoacoustic engine was built by Yazaki et al [3]. This typical arrangement engine utilizes traveling-wave type propagation of sound waves, which propagates through a loop channel. Three main components of the engine, hot heat exchanger, cold heat exchanger, and regenerator are placed in the loop. Thermoacoustic core, that is regenerator, was observed as one of important parameter that roles the ability of the model to generates acoustic power. The characteristic tranverse length of sanwiches solid layer in the regenerator has quadratic effect on the minimum onset temperature ratio, the minimum temperature ratio applied so that a spontaneous acoustic wave oscillates. The engine, which is sets in travelling-wave engine arrangement mode, was succesfully generate about 200 W/m^2 acoustic power. It amplifies acoustic power with gain 1.2, which is means net power of about 20% than those of input acoustic intensity incoming from cold end side of regenerator [3]. High axial avarage velocity causes large viscous losses which in turn significantly reduce the engine efficiency. Backhaust and Swift [4] construct for the first time a torus and resonator type of thermoacoustic Stirling engine, which is known as TASHE (Thermoacoustic Stirling Heat Engine), almost one year after Yazaki et al [2] published their one wavelength looped engine. The Backhaust and Swift's engine is considered as a variant that developed from a single loop engine arrangement, althrough both of them developed separately. Dimensions and performances of TASHE can be found in Backhaust and Swift [4]. The looped tube of the engine is filled with Helium and it works at a frequency of 80 Hz. The engine's efficiency achieved 30%, corresponds to 42% theoritical maximum Carnot efficiency, is higher than other pistonless thermal engine. Apart from the inner working fluid setting prameters, the main construction difference of the two type of engine arrangement is the introduction of resonator branch in the TASHE engine.

A model of a thermoacoustic engine has been built by Nurpatria et al [5], which is designed to be able to utilize the combustion of biomass fuel as a heat source. This engine model has parameters that refer to the advantages of Yazaki et al [3] and Backhaust and Swift [4] engine designs. The special feature of this engine model design is in the arrangement of hot heat exchanger which allows it to receive heat from direct flue gas flow of low-grade biomass combustion. Small scale implemetation of the engine is promising mostly in rural area, considering that abundant availability of low grade biomass such as agricultural waste in that area. The loop of this engine is modeled as continous channel without any bends or channel area change. As the consequences, the worlking fluid inside the loop is flow without experiencing any type of energy loss. This idealalisation behavior is unmatch with the fact that the actual flow undegoes energy loss due to surface friction or pressure drop. The main objective of this paper is to present the improvement results of work in order to take account the energy loss affected by insertion of cone segments model into the current engine model [5].

II. Simulation Modelling

A. Engine Modelling

The scheme of the thermoacoustic engine model presented in this article is shown in Figure 1. The simulation method used to determine the model performances is through one-dimensional Delta EC simulation, conducted in Version 6.2 package of Ward et al [6]. The open source Delta EC software divides the engine body into several individual segments, with the initial simulation position correlated to $x = 0$ in the engine's loop at cross section 2, or marked as point 2 at Figure 1. Acoustic energy is generated in the regenerator (REG), segment 3-4, of the engine. The regenerator material is modeled to be composed from porous material with such a small pore size equivalent to the thickness of thermal penetration depth. The machine loop starts from point 5 to point 2. In this loop, acoustic energy E that flows, varies depending on its precise location in the loop. If the flow losses does not occur, the acoustic energy in the narrow gap at straight channel segment between point 2 and an earlier closest point, for example point 1, also does not change. The same condition also applicable in the short straight pipe segment from point 5 to 6, which is in the x direction flow.

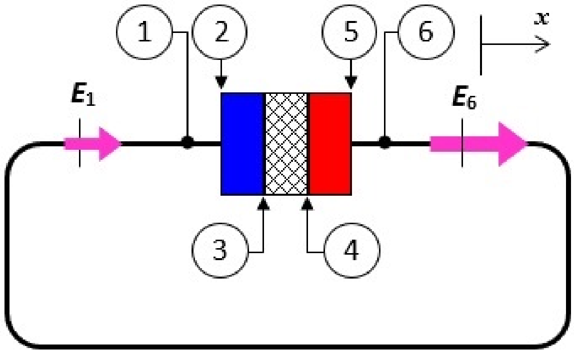

Fig. 3. Schematic of the single looped thermoacoustic engine model

The acoustic energy produced by the regenerator comes from the conversion of heat energy. Heat energy is required to create a working fluid temperature gradient between two end cross section of the regenerator, from point 3 to 4 in figure 1. The working fluid temperature gradient along the regenerator is made possible by the difference in the amount of heat supply in the cold heat exchanger (CHX) and hot heat exchanger (HHX). In Figure 1, CHX located at segment 2-3, and HHX is at segment 4-5. The E_4 acoustic energy amplified by REG that comes out of the HHX flows in the x direction in the loop and becomes E3 feed energy which goes back into CHX, which is re-amplified by REG. A potential acoustic energy loss in the engine's working fluid flow, in terms of decreasing acoustic energy, possibly occur at the interface of two segments with different cross-sectional area. In the case of engine model in Figure 1, if the cross-sectional area of loop A_1 or A_6 are the same as the cross-sectional areas of CHX and HHX, that are A_2 and A_5, then there will be no loss of flow at these two locations.

Acoustic energy that flows throughout all thermoacoustic engine segments which is E in Equation 1, induced by two acoustic wave components, (a) the traveling wave pressure wave p and (b) the volumetric flow rate U. As an exception, acoustic energy generation in the regenerator's pore follows Equation 2, where p and U are also involved. The variables E, p and U are in complex domain. Therefore, differences in p and U oscillations lead to a specific phase at each different location along the engine's body. So that the phase difference also has an effect on the acoustic energy difference in two cone segments placed at two different locations in the engine's loop.

The acoustic energy flowing through a certain segment in the engine model, including the loop segment, is according the equation from Swift [7]. The pressure difference between the two ends of a segment is Δp, the volume flow rate in the segment is U, and θ is the phase angle difference of each p and U oscillation. The acoustic energy flowing in a straight channel segment, for example between points 1 and 2 in Figure 1, is calculated based on the difference pressure between both endpoints of the segments. Equation 1 applies to all segments, except for the regenerator.

$$E = \frac{1}{2}|\Delta p||U|\cos(\theta) \tag{1}$$

As for the regenerator segment only, the calculation of acoustic energy uses Equation 2 [7]. The statement in this equation is in the complex domain, so that the pressure oscillation p and the volume flow rate U are also in the complex domain, so that acoustic propagation of them is represented by the statement of real component, Re[] in terms on the left side, and the first term on the right side, and imaginary component, Im[] in the second right side of the equation.

$$\frac{1}{2}\mathrm{Re}[gpU] = \frac{1}{2}\frac{1}{T_m}\frac{dT_m}{dx}\mathrm{Re}[pU]\mathrm{Re}[f_\kappa] + \frac{1}{2}\frac{1}{T_m}\frac{dT_m}{dx}\mathrm{Im}[pU]\mathrm{Im}[-f_\kappa] \tag{2}$$

Mean temperature of engine is T_m, and positive temperature gradient, (dT_m/dx), introduced to regenerator is enabled by heat rate input Q difference between CHX and HHX. If the CHX is maintain at the ambient temperature, or at the engine's mean temperature, the heat input of the engine is approximated only affected by heat injected into the HHX, Q_H. Thus, the overall engine efficiency is as following equation [4,7].

$$\eta_{H\text{-}A} = (E/Q_H) \tag{3}$$

At positive x direction, acoustic energy always attenuated. The only location acoustic energy is generated is inside regenerator, at its porous filling material. So that the acoustic energy generated by engine E is the amplification of acoustic energy feed that exits from CHX which is equals to that incoming to the regenerator, point 3 in figure 1, into acoustic energy that exits the regenerator at point 4. The overall efficiency is simply the ratio between the two, E and Q_H.

B. Minor Losses

The channel that forms loop in Figure 1 usually changes in diameter at some certain locations to accomodate the difference in optimum diameter of the segments obtained from simulation. The engine model of Nurpatria et al [5], rely on the assumption that the engine loop channel is composed without bends, diameter alteration, or conical segments, except at the interface of loop ends with both of heat exchanger, CHX and HHX. Such type of those ideal loop channel shape is ideal estimation and inpractical to build. The real engine loop channel usually assembled from several single piece of pipes and bends that connected together to form a complete single loop. As a consequence, the engine model must be redefined to be able to represent those various different physical geometries form added to the channel. That more realistic channel model in turn lead to the needs of modelling the flow losses that occurred at those geometries. Flow losses it bends and diameter changes are commonly termed as minor losses.

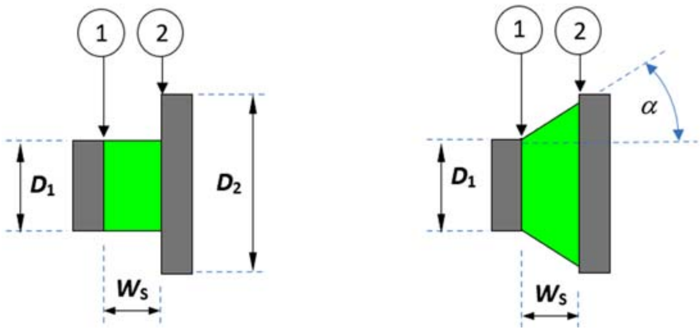

Fig. 4. Geometry comparisson of (a) straight segment, and (b) cone segment

Expression of minor losses (Δp) in the channel of a thermoacoustic engine is adapted from Ward et al [6]. It depends on the minor losses coefficient K, and the flow velocity u. The velocity u in (4) is derived from volumetric flow rate in the complex expression U from (1) or (2), which flows in reciprocal manner regarding to the predefined x direction flow inside the loop channel. As a consequence, numeric value of K factor in Equation (4) should be set differently for either positive x-direction flow ($K+$) or negative x-direction flow ($K-$).

Pressure p in x direction will always decrease due to inner friction between working fluid particles and inner wall surface roughness, and it indicates by minus sign in (4). In conducting the simulation, both $K+$ and $K-$ is set simultaneously following a certain step guide already built-in inside the software [6].

$$\Delta p = -\frac{1}{2} K u^2 \tag{4}$$

This paper presenting the effect of two cone segment that placed separately at two different location along the loop, on minor losses generation. Figure 2 shown scheme and nomenclature of a straight segment (Figure 2a) in comparison with a cone segment (Figure 2b). The first cone segment is at cross section 1b to 2, Figure 2b, and the second one is at 5b to 6 (not shown in Figure 2). Both of cone segments are identical but reverse each other in x direction orientation. The cone diameter, or hydraulic diameter, of the first cone is gradually enlarges from its smallest inner diameter D_1 at 1 to become largest inner diameter D_2 at 2. So that the minor losses coefficient applied to the model in Figure 1 become $K+$ sets at location 1, and $K-$ sets at location 2. In the case of the second cone, $K+$ sets at 5, and $K-$ sets at 6, Figure 1 [6,8]. Point 1 coincide with 1a, and 5 with 5a. This two K different setting correlated to two different type of obstruction losses, gradual cross section enlargement losses and gradual cross section contraction losses, that occur alternately.

TABLE I. SEGMENT PARAMETERS OF DELTA EC MODEL

Segment		Parameter			Setting
		Name	***Symbol***	***Unit***	
1	Cone 1	Length	W_{s1}	mm	12
		Area 1 In	A_1	cm^2	90
		Area 2 Out	A_2	cm^2	100
2	CHX	Length	L	mm	30
		Area 2 In	A_2	mm^2	100
		Area 3 Out	A_3	mm^2	960
3	Regenerator	Length	L	mm	18
		Area 3 In	A_3	mm^2	100
		Area 4 Out	A_4	mm^2	100
		Hydrolic Radius	r_h	micron	58
4	HHX	Length	L	mm	10
		Area 4 In	A_4	mm^2	100
		Area 5 Out	A_5	mm^2	100
5	Cone 2	Length	W_{s2}	mm	12
		Area 5 In	A_5	cm^2	90
		Area 6 Out	A_6	cm^2	100

Table 1 shows geometrical parameter of each main segment of the thermoacoustic engine presented in this paper. Previous engine model loop length, that is length from point 5 to 2 in Figure 1, is 174 cm [5]. The engine loop length of current engine model presented in this paper is also kept at the same loop length. Cone 1 length W_{s1} replaces the same length from 1a to 2 at the straight model. Also, cone 2 length W_{s2} is replaces straight length from 5a to 6.

III. RESULT AND DISCUSSION

Figure 3 shows the acoustic energy E level at various x point along the engine model. The $x = 0$ point is set before CHX, that is point 1 in Figure 1. Each other point shown in this figure is also corresponds to the point shown in figure 1.

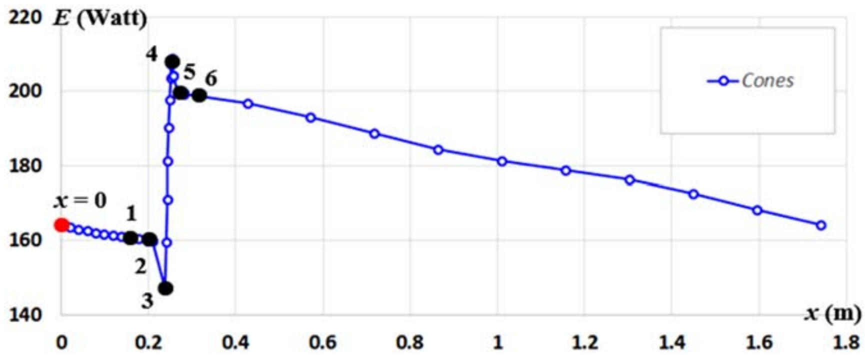

Fig. 5. Acoustic energy inside the engine inserted with two cone segment model

Acoustic energy is generated in the regenerator, according to equation 2, marked by an increase in the level of energy content from point 3 to point 4. This energy comes from heat input that is supplied into the HHX which act as the hot end of temperature. This temperature gradient is maintained relatively constant throughout the conversion process. Figure 3 shows the highest acoustic energy level inside the engine body after two cones inserted is at point 4, E_4 = 204.1 watt. This is correlated to 1.1 watt higher than those before two cones applied, that is with straight segments. In contrary, acoustic energy level step decline takes place at both heat exchangers, the CHX at 2 to 3 of about 17 watt, and the HHX at 4 to 5 of around 4.5 watt. This significant amount of heat exchanger energy loss is due to the fact the working fluid travels across a bundle of 'tube and shell' packing [8]. Acoustic energy along the engine's channel loop is always attenuated, depicted by curve declination from point 6 to engine's end point and from $x = 0$ to point 2 in Figure 3. The attenuation at the whole channel loop segment is addressed as an effect of inner channel wall friction loss [8].

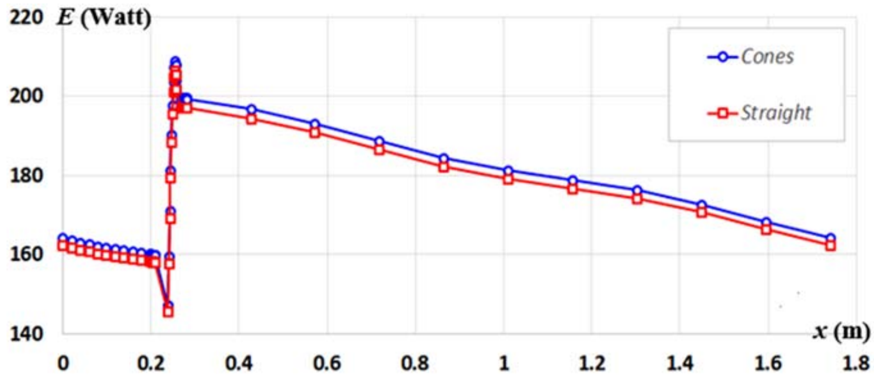

Fig. 6. Acoustic energy inside the engine, (a) straight segment model and (b) cone segment model

Following the above-mentioned acoustic energy level key points at figure 3, acoustic energy evolved at similar manner inside the engine with straight segment. The pattern is the same but with a slightly lower in energy level at almost all any point along the engine's body. From figure 4 is possible to note that the cones insertion lead to the engine performance's improvement. The peak acoustic energy generation by the engine with straight segment is E_4 = 203.0 watt, see table 2, which is lower of about 0.5% compared to the one with cones. Although that number considered as a tiny fraction, but the cones existence effect is observed in both curves of figure 4.

TABLE II. PERFORMANCE PARAMETERS OF THE ENGINE MODELS

Segment		**Parameter**			**Straight**	**Cones**
		Name	***Symbol***	***Unit***		
1	Global Parameter	Heat to Acoustic Efficiency	η_{H-A}	%	6.97	7.01
		Carnot Efficiency	η_{CAR}	%	51.67	51.60
		Rasio (η_{H-A} / η_{CAR})	Rasio η	%	13.49	13.58
3	Regenerator	E_3 In	E_3	Watt	146.1	147.0
		E_4 Out	E_4	Watt	203.0	204.1
		E net	E	Watt	56.9	57.1
		Ratio (E net / E_3)	Ratio E	%	38.9	38.9
4	HHX	Heat Input	Q_H	Watt	815	815
		E_4 In	E_4	Watt	203.0	204.1
		E_5 Out	E_5	Watt	198.5	199.6
5	Cone 1	Equation 4, K at x +	K +	-	-	0.80
		Equation 4, K at x –	K –	-	-	0.10
6	Cone 2	Equation 4, K at x +	K +	-	-	0.10
		Equation 4, K at x –	K –	-	-	0.80

Interesting to notice that the external energy imposed to the two engine model variants in Table 2, straight and cones, is the same i.e. Q_H = 815 watt. The cones model effectively converts the same amount of energy input into a higher acoustic energy generation. From Q_H = 815 watt, straight model regenerator's generates net acoustic energy E net = 56.9 watt at $\eta_{H\text{-}A}$ = 6.97%. On the other hand, from the same Q_H cones model generates E net = 57.1 watt at $\eta_{H\text{-}A}$ = 7.01%. Each cone sets with minor losses coefficient as shown in table 2. The cone 1 is enlarge gradually as x proceed in positive direction, so that the K+ is sets 0,80 as it act as cross-sectional gradual enlargement obstruction. The K– is 0,10 as it acts as cross-sectional gradual contraction obstruction. The cone 2 sets with switched K+ and K– value due to its orientation that enlarge gradually in negative x direction [8].

IV. CONCLUSION

The cone segments model inserted into the engines model is capable to lower the energy losses which in turn improves the overall engine's performance. The model is able to convert the heat energy into acoustic energy more effective. A 815 watt heat energy converted into 57.1 watt acoustic energy, that equals to 7.01% efficiency. The straight model converts a 815 watt heat into 56.9 watt acoustic energy, which is equals to 6.89% efficiency. The overall heat to acoustic conversion efficiency of the model is then slightly increase into 7.01% and that is approximately 1,7% improvement.

ACKNOWLEDGMENT

The author takes this opportunity to thank all those who have contributed in preparation and writing of this article, including head and staffs of Computational and Design Laboratory of Mechanical Engineering Department Mataram University.

REFERENCES

[1] A. Sertolli, Z. Gabnai, P. Lengyel, and A. Bai, "Biomass potential and utilization in worldwide research trends - A bibliometric analysis," Sustainability, vol. 14, no. 5515, 2022.

[2] M. Elferink, and T. Steiner, "Thermoacoustic waste heat recovery engine - Comparison of simulation and experiment," Proceedings of Meetings on Acoustics, vol. 35, no. 065002, 2019.

[3] T. Yazaki, A. Iwata, T. Maekawa, and A. Tominaga, "Traveling wave thermoacoustic engine in a looped tube," Physical Review Letters, Vol. 81, No. 15, October 1998.

[4] S. Backhaus, and G.W. Swift, "A thermoacoustic Stirling heat engine - Detailed study," Journal Acoustic Society of America, Vol. 107, No. 6, June 2000.

[5] Nurpatria, I G.B. Susana, I W. Joniarta, Nurchayati, and H.S. Tira, "Peningkatan efisiensi konversi energi mesin termoakustik," Prosiding SAINTEK LPPM Universitas Mataram, Vol. 3, pp.369-373, Januari 2021.

[6] B. Ward, J. Clark, and G. Swift, Design Environment for Low-amplitude Thermoacoustic Energy Conversion (Delta EC) - Version 6.2 Users Guide, Los Alamos National Laboratory, December 2008.

[7] G Swift, Thermoacoustics - A unifiying perspective for some engines and refrigerators, Condensed Matter and Thermal Physics Group - Los Alamos National Laboratory, 5th Draft, 2001.

[8] M. Yiyi, X. Xiujuan, Y. Shaoqi, and L. Qing, "Study on minor losses around the thermoacoustic parallel stack in the oscillatory flow conditions," Physics Procedia, No. 67, pp.485-490, 2015.