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Study on the looped-type thermoacoustic prime mover for the high efficient and practical system

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A thermoacoustic prime mover, due to its simple structure, would serve as very desirable systems because it can be driven with the waste heat such as an exhaust gas from engines, and with heat from the nature such as sunlight and a geothermal heat. The advantages of this prime mover are the flexibility for various heat sources as an external engine and a possibility as the cost effective system due to simple structure. On the other hand, the energy conversion from waste heats to more effective energy such as motion energy or electric energy is desired in the automotive area because of demands of improvement of fuel efficiency. In this research, our interests focused on the performance improvement of looped-type thermoacoustic prime mover by varying stack configuration, inserting membrane to cut off the DC flow and adopting equipment of phase adjustment between pressure and velocity of gas oscillation. The experimental setup we use here is operated under the condition of a 4.2m loop length, the working fluid is argon, the 75Hz operating frequency and stacked screen mesh as a stack configuration. To improve the total thermal efficiency, various efforts have been made experimentally to grasp the optimization of stack structure which plays an important role to energy conversion. Finally, discussions on the future application of prime mover aiming to utilize the waste energy of exhaust gas are made and, by installing a membrane of natural rubber inside the tube, the acoustic intensity has increased by 20%.

1 Introduction

In recent years, the problems which affect the global environmental system such as the global warming and energy depletion become serious. For the reason of this, the utilization of waste energy like waste heat is getting necessary to solve these problems. One of the solutions for these situations, the thermoacoustic system has a very attractive characteristics for 2 reasons; 1. because it drives as external combustion system, it can use many kinds of heat source ; 2. It has simple structure so the cost for the system construction is low. The thermoacoustic phenomenon can convert from heat energy to acoustic energy and vice versa, and the energy can be transferred as an acoustic sound adiabatically so in the wide area like tube the sound will not exchange energy with solid wall by heat exchange but it will exchange energy with solid called "stack wall" by halfway heat exchange.

In this paper, we adopt the travelling wave type thermoacoustic prime mover system with looped-configuration and with this system for the improvement of the performance of this system we vary stack configuration, inserting membrane to cut off the DC flow and adopting equipment of phase adjustment between pressure and velocity of gas oscillation. Then discussions on the future application of prime mover aiming to utilize the waste energy of exhaust gas are made and finally we extend this into the electric generation system for the enhancement of fuel consumption efficiency.

2 Experimental apparatus

The Figure 1 shows the schematic of the experimental apparatus. The length of the loop tube is 4.2m, the outer diameter of the tube is 60.5mm and the inner diameter of it is 52.7mm of stainless steel. The length of the long side of the loop is 1233mm and the short side of it is 700mm. When the working gas is Argon, the frequency of the system is 75 Hz. 12 pressure gauges are installed along the tube length and the acoustic power can be estimated with the measured results by 2 sensor method.

The Figure 2 shows the detail of the stack. To investigate on the method of the heat exchanger, we adopt 3 types of heat input method, (a) is direct heat input method, (b) is indirect heat input method and (c) is semi-direct heat input method. The type(a) is operated that the sheathed heater is inserted in the tube and directly heats up the working fluid and stack, and the type(b) is operated that the ceramic heater is twisted around the tube and indirectly heats up the working fluid and stack and the type(c) is operated that inside the tube the solid device made of copper(called copper block) for the enhancement of heat exchange between solid and working gas is installed and the sheathed heater is twisted around the copper block and is heated up by the heater then transfers heat to the working gas. The materials and configurations of the stack are the important parameter of this research and are shown in each following chapter. We call the left side of the stack in Figure 1 as "Work Transfer Tube(WTT)" and 2 heat exchanger by water cooling are used like in Figure 1 & 2.

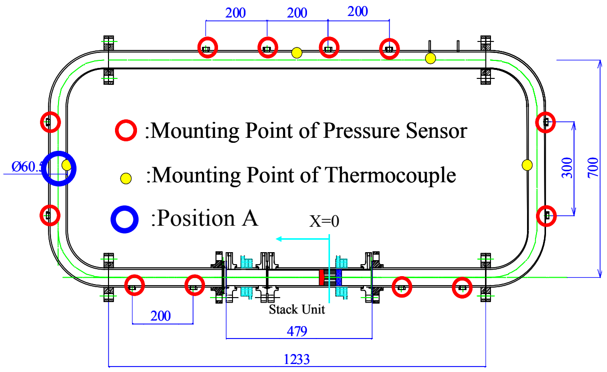
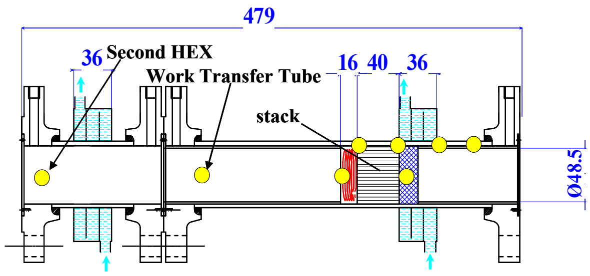
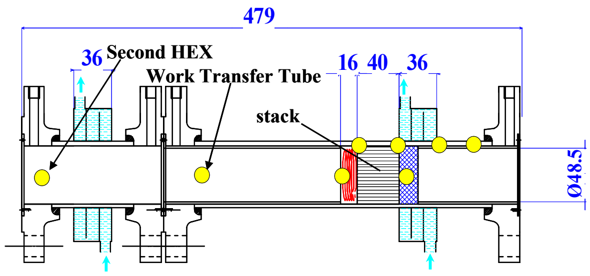


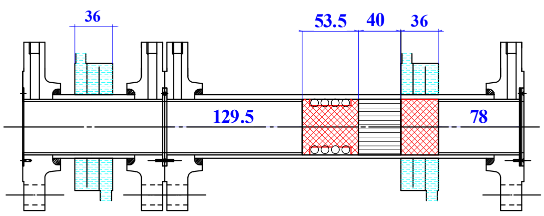
Fig.1 Schematic of Experimental Apparatus



(a) Direct Heat Input



(b) Indirect Heat Input



(c) Semi-direct Heat Input

Fig. 2 Detail View of Stack Unit

3 Results and discussions

3.1 Direct heat input

3.1.1 Influence of the stack configuration of screen mesh

The mesh of # 30 was compared from enclosed pressure 300kPa in the condition of 600kPa with the outcome of an experiment of the mesh of # 40. It became a result large even if # 30 compared it by the value of which pre-charge pressure in sound strength with Figure 3(c) though it was a mesh of # 30 and # 40 and there was no big difference in the size of the pressure amplitude and the flow velocity amplitude than Figure 3(a) and (b). This result is considered from the value of the phase lag φ of $\omega\tau_\alpha$, the pressure oscillation, and the flow velocity oscillation. Figure 4 shows $\omega\tau_\alpha$ in each condition and the calculation result of φ.

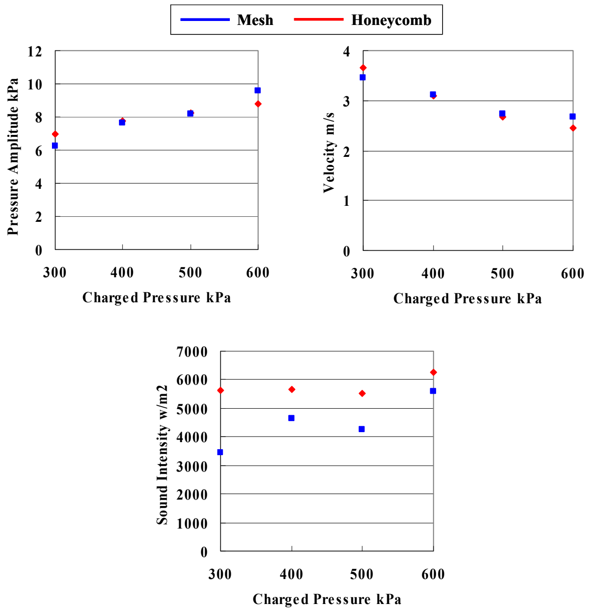


Fig.3 Experimental Results (#30 & #40)

An $\omega\tau_\alpha$ is a dimensionless number shown by the product at the circular frequency and the easing time. An ωτ can be shown by squaring the ratio of hydraulic radius r_0 of the stack to the boundary layer thickness. Therefore, when the boundary layer thickness grows, the value of ωτ becomes small.

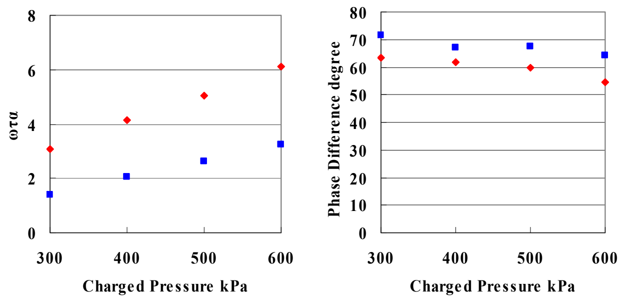


Fig.4 $\omega\tau_\alpha$ & Phase Difference (#30 & #40)

An ωτ is theoretically assumed that a heat exchange highly effective by about one is done. However, when Figure 4(a) was seen, an ωτ greatly exceeded one, and # 30 that sound strength was larger became a result more than the result of # 40 by the value of ωτ in each condition.

On the other hand, when the phase lag of Figure 4(b) is seen, # 30 is a value that is smaller than # 40. Because the value of the cosine of the phase lag φ in addition to the size of the pressure amplitude and the size of the flow velocity amplitude influences the calculation of sound intensity, sound intensity in one with a small phase lag grows. Therefore, it has been understood that the control of the phase lag is necessary to increase sound intensity. The viscous resistance is thought as a factor that influences the size of the phase lag. The passage diameter of # 40 is smaller and the viscous resistance is larger than #30.

3.1.2 Intercept of the DC mass flow

To intercept the mass flow that effused from the high temperature edge to WTT, the membrane(rubber film) was set up. The heat input was assumed to be a direct input (192W input) and the location of the membrane(rubber film) is set at 289mm from the low temperature edge of WTT.

The temperature history of the high temperature edge and WTT was summarized in Figure 5, and the comparison by the presence of the membrane was summarized and the pressure amplitude and sound intensity at 2000 time of the second were summarized from the insertion heat beginning in Table 1. Sound intensity uses the value of Figure 1 inside point A.

The uptrend of a rapid descent and the WTT temperature of the high temperature edge temperature after it had oscillated being seen when the rubber film was non-installed was controlled by inserting the rubber film. Thus, the effect of physically intercepting the outflow of heat by the rubber film was proven. This result improves by 18% in the amplitude and improves by sound strength by 53%.

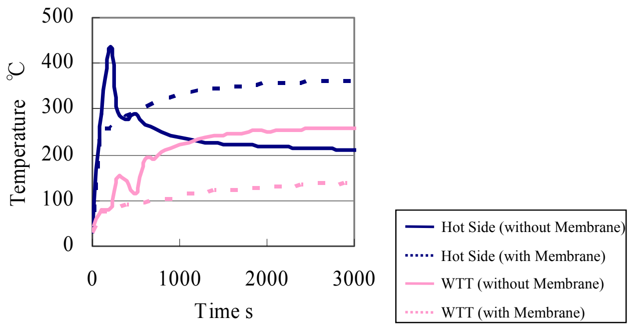


Fig.5 Temperature History(With & Without Membrane)

Table 1 Experimental result(with & without Membrane)

Membrane	Pressure Amplitude kPa	Sound Intensity W/m^2
without	10.3	5452
with	12.2	8581

3.2 Indirect heat input

3.2.1 Influence of stack material

Experiment to make an effective thermal conductivity a parameter(from 120 to 175mW/m/K) by changing the stack material was done as Table 2. Prediction expression by means of with regular heating methods, that had been obtained by Tanaka's et al. was used for the calculation of an effective thermal conductivity.

Table 2 Characteristics of Mesh

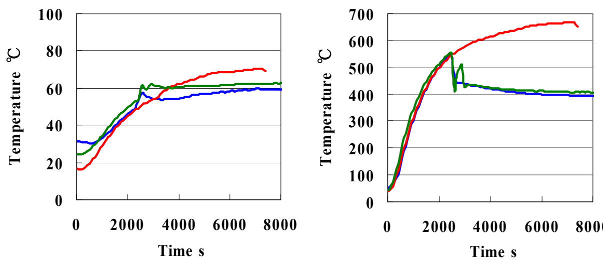
Material	Structure	Porosity	Hydro Dynamic Radius mm	Thermal Conductivity W/(m·K)	Effective Thermal Conductivity mW/(m·K)
Stainless	#30(0.29)	0.72	0.365	16.3	120.7
Nickel				90.7	149.9
Copper				401	175.3

The outcome of an experiment after 8000 seconds of the insertion heat beginning to which the temperature of each part is steady enough, is arranged and the temperature history on the high temperature edge and the low temperature edge is arranged to Figure 6 and in Table 3.

As a result, the pressure amplitude and sound intensity's growing in order of SUS>Ni>Cu resulted. It has been understood that the one with a small effective thermal conductivity is suitable from growing of an effective thermal conductivity in Table 3 in order of SUS<Ni<Cu in the selection of the stack material, considering the size of an effective thermal conductivity.

Table 3 Experimental Results (8000s)

Stack Material	Charged Pressure kPa	Pressure Amplitude kPa	Sound Intensity at Ch1-2 W
SUS	400	15.33	23.66
Ni		14.77	20.61
Cu		7.72	3.04



(a) Cold Side (b) Hot Side

Fig.6 Temperature History

3.2.2 Influence of stack length

The method of inputting heat was indirect and the experiment that changed the stack length from 40mm to 80mm at intervals of 10mm was done. The result of sound intensity and the pressure amplitude in each length was arranged to Figure 7.

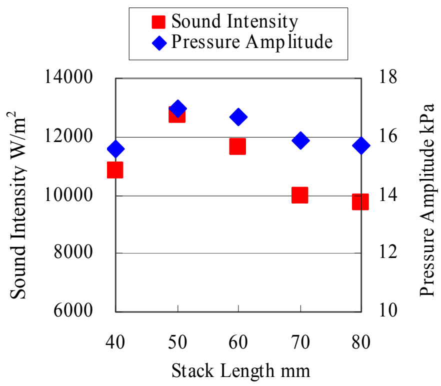


Fig. 7 Sound Intensity & Pressure Amplitude vs. Stack Length

It both becomes the maximum at 50mm as a result, the difference of 23% was seen in sound intensity as for the amplitude and sound intensity though the amplitude was a difference of several % compared with the result at 80mm. Because the duct in the stack part has narrowed from this very much, we have understood a stack long more than the necessity becomes a big loss factor.

Next, the temperature history on the high temperature edge and the low temperature edge when it is changed into Figure 8 that the stack length from 40 to 80mm is shown.

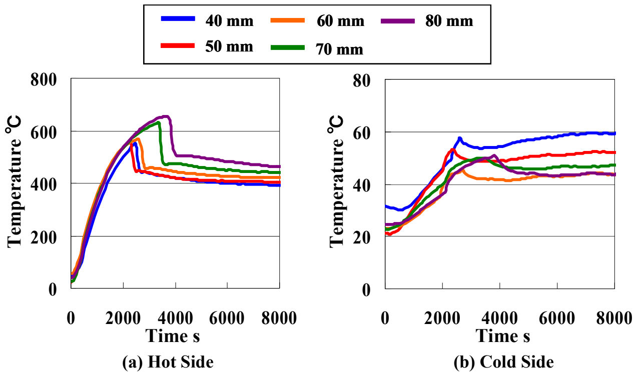


Fig.8 Temperature History

As a result, the temperature decreases rapidly at the same time as the oscillation's beginning in the high temperature edge, and it is understood to be steady from there. As for the one with short stack length, it is understood that the temperature rise or more is large though the temperature rises at the same time as the oscillation's beginning in the low temperature edge compared with it once, and it stabilizes there. This reason is thought that it is because heat transmits to the low temperature edge without doing the interchange of heat in the stack enough. Therefore, it is thought that it became a great result in respect of sound strength (conversion efficiency) compared with time when 50mm the stack length is 40mm.

3.3 Semi-direct heat input

3.3.1 Influence of the amount of heat input

It experimented when the insertion calorie was changed from 300 to 700W with the film inserted by the indirect heat input method. The insertion position of the film is 337mm.

Figure 9 shows the temperature history on the high temperature edge in each amount of the heat input. Moreover, the characteristic of the output to the amount of the heat input is shown in Figure 10. It has been understood for the high temperature edge temperature to rise with an increase in the amount of the heat input, and to do a steady oscillation in the state of about 800degC by the input of about 400degC and 700W in the input of 300W. Therefore, it is understood that an oscillation steady from the level of the idling temperature of the gas to the level of the temperature of the gas of a high load operation is possible. In addition, it is understood that sound strength and the pressure amplitude increase to the amount of the heat input almost proportionally.

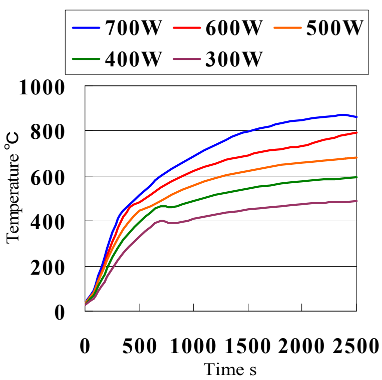


Fig. 9 Temperature History at Hot Side

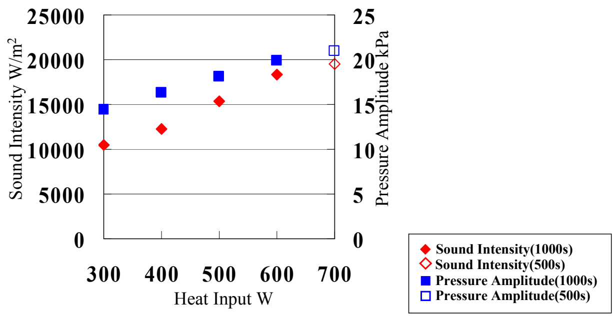


Fig.10 Sound Intensity, Pressure Amplitude vs. Heat Input

4 View in the future

For method of installing vehicle, it is assumed to set up the partition type heat exchanger in orthogonal shape to the rejection tube after the catalyst, and to install it under the body in shape to enclose a central muffler. Moreover, the engine displacement assumed the SUV car that there is greatly room in the height of the lowest ground to the model. The total length can compose the looped tube of about from 3m to 4m of the catalyst, considering the distance to a rear muffler and the distance with the side member.

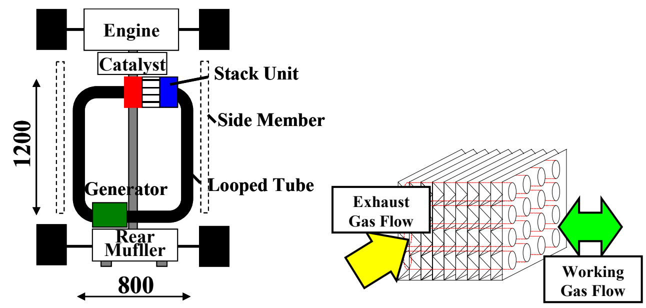


Fig.11 Image of System Installation/Hot Heat Exchanger

5 Conclusion

(1) The mass flow is intercepted by inserting the rubber film, and sound strength has increased by a factor of 1.5.

(2) Many of pressure losses of the thermoacoustic prime mover occur in the stack, and a too long stack becomes a big loss factor.

(3) It was shown to drive and to oscillate stably in a wide temperature span.

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