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Influence of Material Used for the Regenerator on the Properties of a Thermoacoustic Heat Pump

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Research in termoacoustics began with the observation of the heat transfer between gas and solids. Using this interaction the intense sound wave could be applied to create engines and heat pumps. The most important part of thermoacoustic devices is a regenerator, where press of conversion of sound energy into thermal or *vice versa* takes place. In a heat pump the acoustic wave produces the temperature difference at the two ends of the regenerator. The aim of the paper is to find the influence of the material used for the construction of a regenerator on the properties of a thermoacoustic heat pump. Modern technologies allow us to create new materials with physical properties necessary to increase the temperature gradient on the heat exchangers. The aim of this paper is to create a regenerator which strongly improves the efficiency of the heat pump.

Keywords: thermoacoustics, heat pump, engines, traveling wave.

1. Introduction

Thermoacoustics refers to a physical phenomenon by which a temperature difference can create and amplify sound waves and *vice versa*: the sound wave causes the formation of the temperature difference between the two heat exchangers. The principle of operation equipment involves the use of a cyclic interaction between the acoustic waves and gas particles. Under the influence of an acoustic wave, gas particles oscillate near the equilibrium position causing perturbations of pressure and displacement. In thermoacoustic devices, the acoustic wave is brought to interact with the porous structure, called regenerator. The regenerator is made of a material with a much higher heat capacity compared to the gas medium through which the sound wave propagates. The function of regenerators in thermoacoustic systems is an exchange and temporary storage of heat. A thermoacoustic layout can be generally divided into two segments:

- the part containing a thermodynamic regenerator, two heat exchangers and a thermal buffer column;
- the acoustic system that provides adequate conditions for the acoustic wave (a waveguide and sound source).

The people who worked as glassblowers were the first to observe the thermoacoustic effect. They noticed that the heated pipes for blowing glass made sounds. In 1777, Byron Higgins observed that placing the flame at both ends of an open tube resulted in the appearing of an audible sound. Another described example of this phenomenon is the P.L. Rijke pipe reported in 1859 (Ward, Swift, 1996). He observed that placing hot metal at the bottom of both ends of an open tube leads to an emergence of strong oscillations of gas molecules. The tube generates a sound only at the vertical orientation. Rijke's tube closed at one end can generate a sound if the end is heated. This phenomenon was observed by a German physicist Sondhauss. Currently the Sondhauss Tube is known as the first heat engine (transformation of thermal energy into the acoustic wave – mechanical work).

After discovering the phenomena mentioned above, it was also found that they are reversible, i.e. acoustic vibrations can be produced by the heat flow, or *vice versa* – a heat flow can be produced by acoustic vibrations.

2. Classification of thermoacoustic devices

Devices in thermoacoustics can be classified according to the type of operation (engines, heat pumps), used materials (regenerators, stacks), and with respect to the type of acoustic wave (standing and running waves). According to Garrett thermoacoustic devices can be divided in the following way:

- engines with a standing wave;
- heat pumps working with a travelling wave;
- engines with a travelling wave;
- heat pumps working with a standing wave.

2.1. Classification of devices with respect to the type of wave

Waves can be classified according to the phase difference between the sound pressure p and the acoustic velocity v (Dobrucki, 2007). Ceperley (1979; 1982) reasoned why running waves are more appropriate in thermoacustic processes. Thermoacoustic devices based on a travelling wave feature an advantage that the pressure and velocity are in phase while the wave passes through the regenerator (Backhause, 2002). The gas enters a cycle of compression, heating, expansion and cooling, similar to the cycles in Stirling or Carnot engine.

Because the pores in the regenerator are small, as compared with the thermal penetration depth parameter ($r_h \ll \delta\kappa$), the thermal contact between the particles of gas and the regenerator elements will be almost perfect (Schutte, 2009). As a result, there is a constant exchange of heat between the gas and the material that takes place over a vanishingly small temperature difference, which causes a slight increase in entropy.

Figures 1 and 2 explain why the hydraulic radius r_h must be substantially smaller than δ_κ If the thermal contact is poor ($r_h \simeq \delta_\kappa$), heating and cooling are delayed and the device using traveling waves works ineffectively. The ineffective work of the thermoacoustic device contributes to the shifting of 2 and 4.

This phenomenon can be used to make the work of a thermoacoustic device more efficient, provided that the traveling wave is changed into a standing wave.

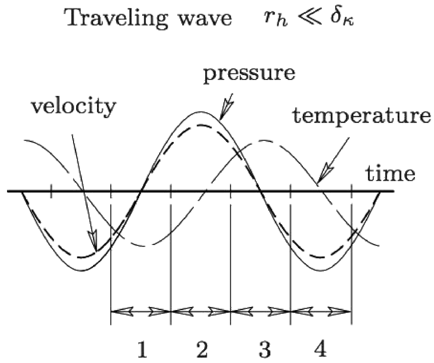

Fig. 1. Pressure and acoustic velocity as a function of time for a travelling wave ($r_h \ll \delta_\kappa$).

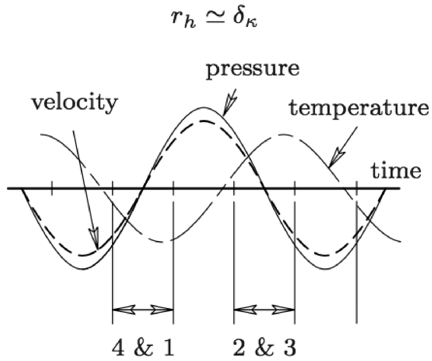

Fig. 2. Pressure and acoustic velocity as a function of time for a traveling wave ($r_h \simeq \delta_\kappa$).

If the wave propagates in the direction of the temperature gradient, the system works as an engine. However, if the propagation direction is opposite to the gradient of temperature, the system works as a heat pump.

3. Measurement arrangement

The measurement setup is shown in Fig. 3. Since the measurements are time-consuming, the measurement position is fully automated. The whole measurement is being controlled by a computer with software created in LabView.

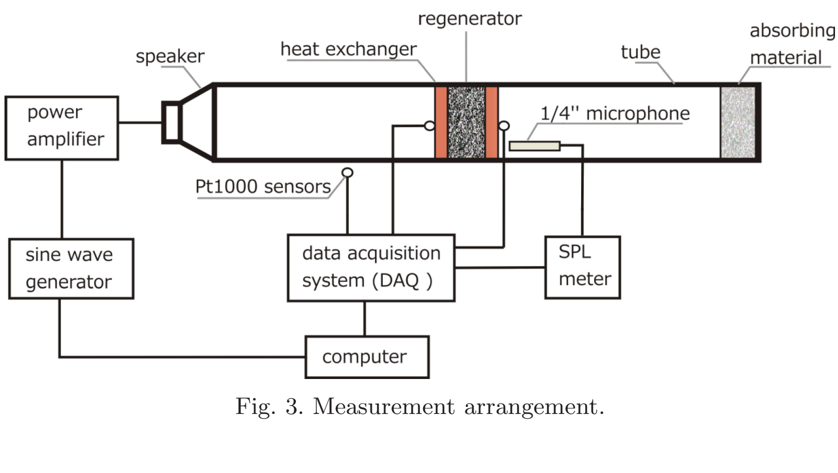

Fig. 3. Measurement arrangement.

The materials used to build the regenerator were supplied by the University of Twente (Netherlands). The following materials have been tested: aluminum, steel, politetrafluoroethylene (PTFE), rockwool, glasswool.

The material shown in Fig. 4 is made of aluminum molded foam.

Fig. 4. Left – aluminum, right – enlargement of the material.

The material shown in Fig. 5 was cut from a grid made of steel wire with the diameter of 0.01 mm.

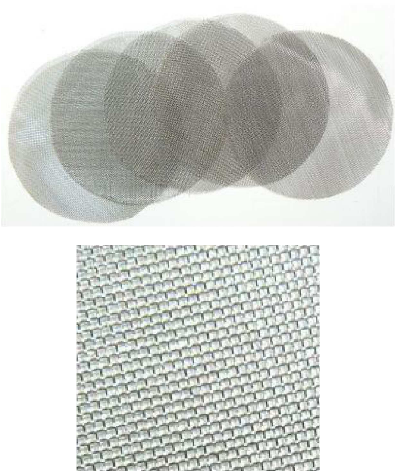

Fig. 5. Top – steel, bottom – enlargement of the material.

The material shown in Fig. 6 was made of politetrafluoroethylene. For the improvement of the thermoacoustic properties of the material, there have been drilled holes with the diameter of 0.01 mm. If these holes are closed the material will lose its improved properties.

Fig. 6. Material – politetrafluoroethylene.

a) b)

Fig. 7. Material: a) rockwool, b) glasswool.

A heat exchanger is a piece of equipment built for an efficient heat transfer from one medium to another. In the described thermoacoustic heat pump, heat exchangers are used to inject and remove heat from the system. Heat exchangers are made of copper. This material features very good thermal conductivity characteristics necessary for efficient operation of the entire device. The heat exchanger is shown in Fig. 8.

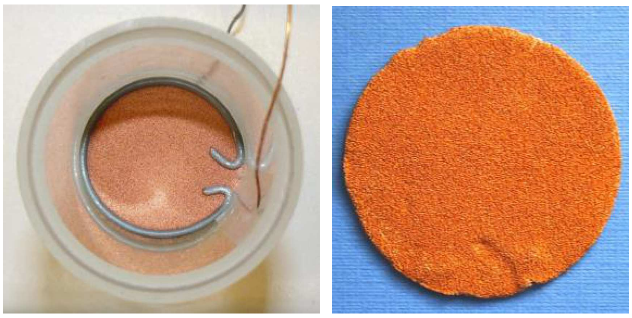

Fig. 8. Heat exchanger.

A modular design allows to create regenerators of any thickness. It allows to verify the influence of thickness on the differences in temperature between hot and cold heat exchangers. The example regenerator module is shown in Fig. 9.

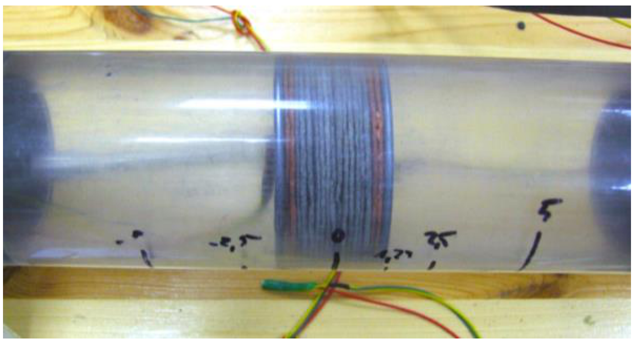

Fig. 9. Regenerator module – aluminum width 2005 mm.

4. Results

A single measurement point should take about 5.5 minutes to assure the stabilization of temperature on the heat exchangers. The sound pressure level was measured with a 1/4″ microphone at the cold heat exchanger. The measurements were carried out for the pressure level of 140 dB. In order to match the impedance at the end of the waveguide, the absorbing material with absorption coefficient close to unity is attached to its end.

Removal of the absorbing material of the pipe causes formation of standing waves. That is the reason why for frequencies above 150 Hz the device does not work properly. This relationship is shown in Fig. 10.

Figure 11 shows the dependence of the absorption coefficient on the frequency.

The temperature difference between the hot and cold ends of the heat exchanger is shown in Fig. 12.

One can see the importance of the regenerator in the thermoacoustic device but a more important thing is the particular material it was made of.

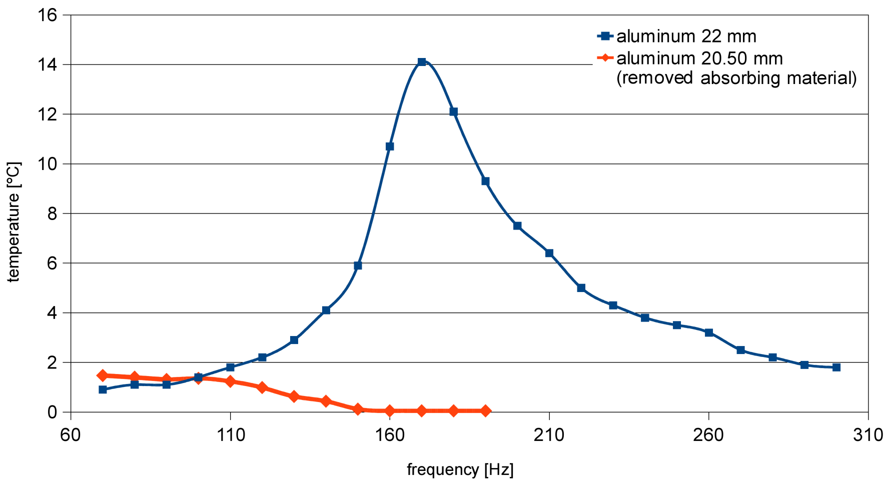

Fig. 10. Temperature gradient as a function of the frequency depending on the impedance matching waveguide.

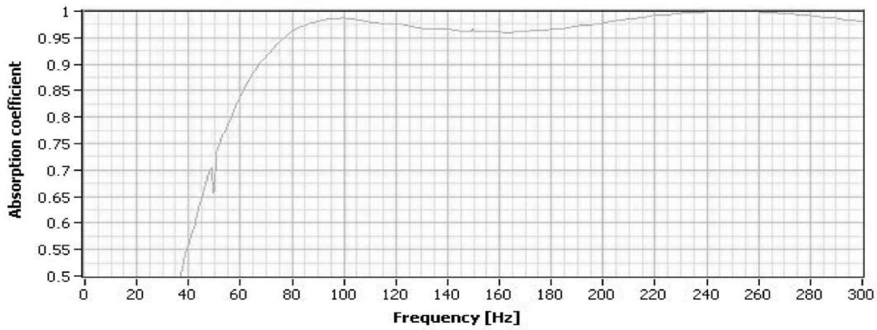

Fig. 11. Dependence of the absorption coefficient on the frequency for the absorbing material at the end of a tube.

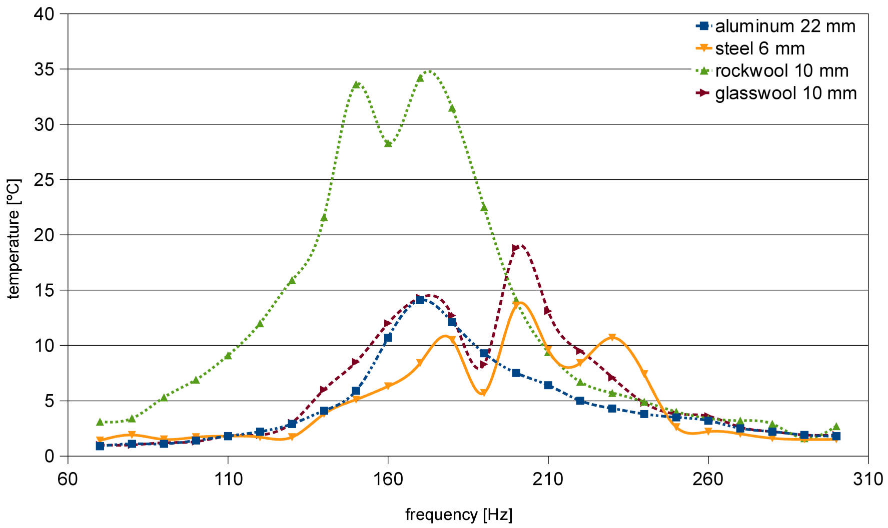

Fig. 12. Temperature gradient as a function of the frequency depending on the material of the regenerator.

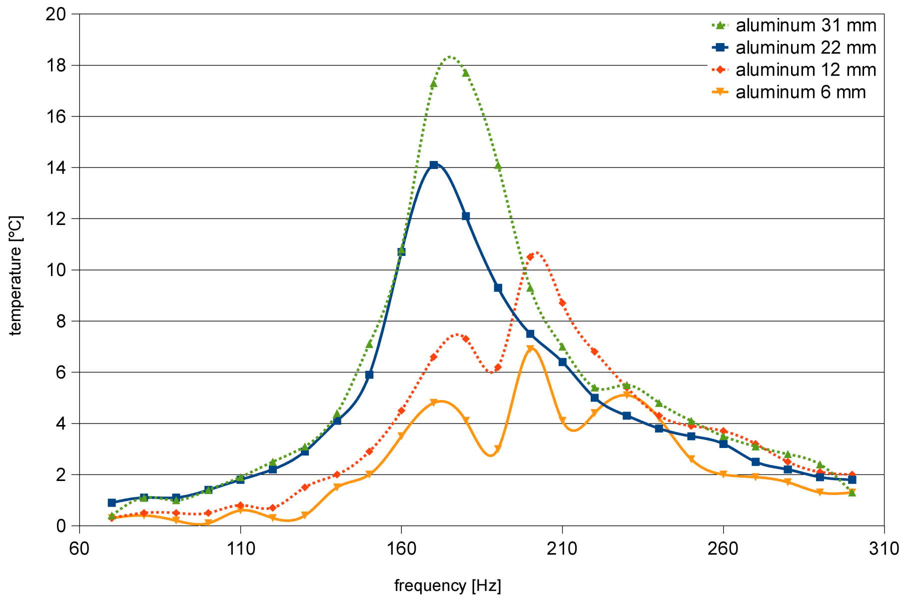

Fig. 13. Temperature gradient as a function of the frequency, depending on the width of the regenerator, material – aluminum.

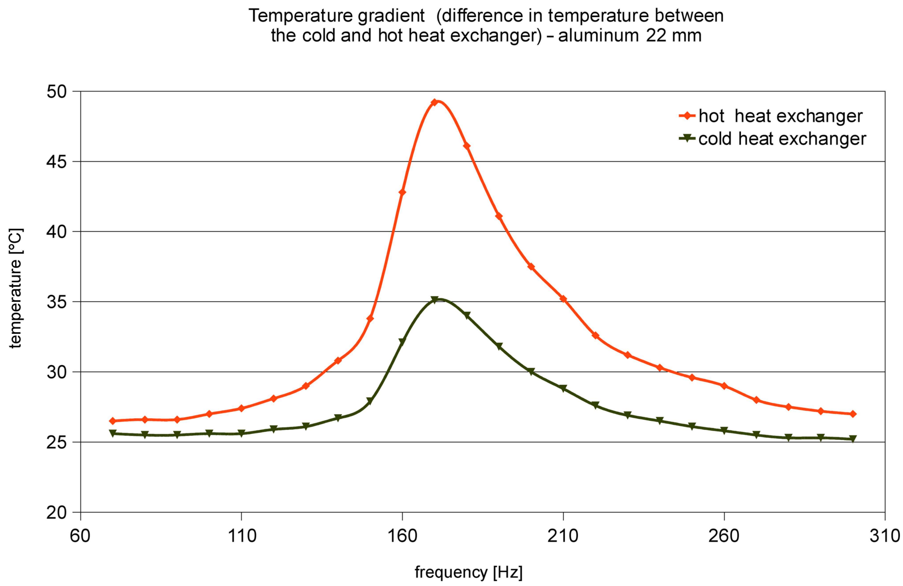

Fig. 14. Regenerator temperature as a function of the frequency.

Figure 13 presents the results of the temperature gradient as a function of the frequency depending on the width of the regenerator. One can see the relation between the width of the regenerator and the frequency bandwidth where maximum temperature differences appear.

Figure 14 shows the temperature of the hot and cold heat exchangers as a function of the frequency.

5. Conclusions

Comparing the present results with the data obtained before the modification of the measuring arrangement (Janowicz, 2011; Dobrucki *et al.*, 2012) significantly important differences can be observed. These differences result from a change of an acoustic pressure level place (the measurement of pressure on the cold heat exchanger) and the use of accurate measuring devices (for example: the use of PT1000, which has greater sensitivity and accuracy as compared to k-type thermocouples used in previous measurements). In Table 1 the results obtained in the study by Janowicz (2011) are presented.

The maximum values of temperature differences between the hot and cold heat exchangers for the tested materials are summarized in Table 2.

Table 1. Summary of the results – Janowicz (2011).

material	width [mm]	f [Hz]	t2-t1 [°C]
aluminum	6.0	280	5.8
steel	6.0	280	9.8
glasswool	40	280	4
rockwool	23	280	18

Table 2. Summary of the results.

material	width [mm]	f [Hz]	t2-t1 [°C]
aluminum	31	180	17
	22	170	14.1
	12	200	10.5
	6	200	6.9
steel	6	200	6.9
glasswool	18.8	200	18.8
rockwool	10	170	34.2
PTFE	10	120	3.4

Comparing the results it can be seen that the implemented modifications significantly improved the obtained temperature gradients.

As it can be seen the best properties were obtained for aluminum and mineral wool: the temperature differences at both ends of the regenerator reached the value of 34°C. Much worse properties were observed for PTFE and glasswool, for which at frequencies higher than 120 Hz, the temperature changes could not be observed. This is caused by the lack of transparency for an acoustic wave.

These studies are the beginning of work on a heat pump In the future the results may support the construction of a thermoacoustic engine. In order to optimize the geometric dimensions of the regenerator, it is necessary to measure the gas flow resistivity of compared materials.

The results can be used to create the optimal material needed to build the regenerator. At the present state the temperature differences in the heat exchanger may reach the value of about 35°C.

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