EPJ Web of Conferences **67**, 02126 (2014)
DOI: 10.1051/epjconf/20146702126

Difference between working gases in thermoacoustic engine

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Abstract. Presented paper includes description of design and assemblage of experimental device for evaluating difference between thermoacoustic device in which was used as working gas air and device in which was used as working gas helium.

1 Introduction

The interaction of heat and sound has been a subject of interest to scientists since 1816, when Laplace [1] corrected Newton's first theoretical calculation of the speed of sound in air. [2] Newton assumed that the acoustic expansions and compressions of the gas occurred isothermally, without any associated variations in the temperature of the gas.

Laplace included the effects of the changes in gas temperature that accompany the adiabatic expansions and compressions of the sound wave and derived the correct result for the adiabatic sound speed that was 18% faster than Newton's isothermal result. These thermal effects, which accompany sound waves, are essential to the operation of thermoacoustic engines and refrigerators. [3]

The term "thermoacoustics" was introduced by Nikolaus Rott, In the literal sense, Rott's claim is entirely justified, since the field is concerned with transformations between thermal and acoustical energy.

A detailed theoretical analysis of standing wave systems, based on the linear acoustics model was performed by Swift [4], who also provided some examples of the early developments at Los Alamos National Laboratory. He also provided a detailed analysis of a practical standing-wave engine where 7000W of thermal energy was converted to 630W of acoustic power [5].

Currently is engaged in thermoacoustic Los Alamos National Laboratory, University of Utah, University of Manchester, National Taiwan University and many other universities and research centres around the world.

2 Theory of thermoacoustic engines

Thermoacoustic devices are using simple design and reliable device, which are using interaction between heat and acoustics for energy conversion [4].

Between advantages of thermoacoustic devices belongs simple design. Thermoacoustic devices do not contains any moving parts, like are shafts, bearings, etc.

For operation that devices are not necessary any special, expensive or dangerous component materials, refills or lubricants. Hence are thermoacoustic devices therefrom view more nature friendly and cheaper for production, than other refrigerators or electric generators.

In view of possibility operation with low temperature gradient, is possible utilize waste heat from a lot of industrial and energetic processes.

Between disadvantages of thermoacoustic devices belongs fact, that currently the majority of thermoacoustic devices have low efficiency. Reason of this is that thermoacoustic phenomena is currently still in research stage.

But it is possible assume that efficiency will increase and thermoacoustic engines and prime movers start be more often used in practical applications.

2.1 Schematic and description of a thermoacoustic device

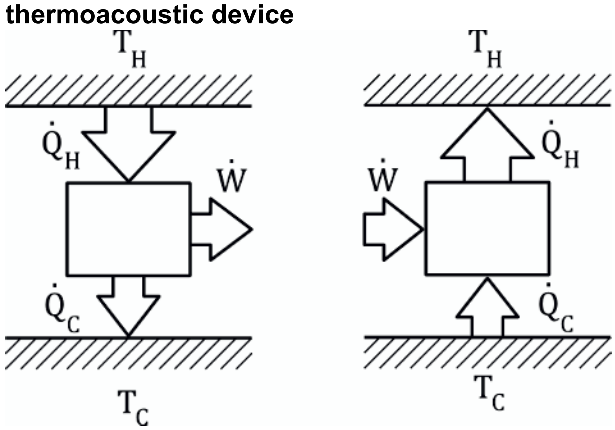

Figure 1. Schematic of function of thermoacoustic engine (left) and thermoacoustic heat pump (right)

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In thermoacoustic engines (Figure 2), heat $\dot{Q}_H$ moves from a hot heat exchanger at a higher temperature T_H to cold heat exchanger at a lower temperature T_c to produce acoustic energy $\dot{W}$ (which can be converted into another type of energy using, for example piezoelectricity), where is heat $\dot{Q}_C$ moved out.

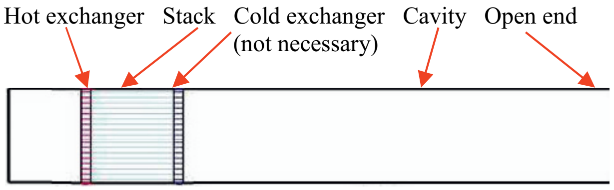


Figure 2. Schematic of thermoacoustic engine

In thermoacoustic heat pumps and refrigerators (Figure 3), is acoustic energy $\dot{W}$, that is produced for example by loudspeaker or by another thermoacoustic engine, used to pump heat $\dot{Q}_C$ from a cold heat exchanger at temperature T_c to a hot heat exchanger at higher temperature T_H where is obtained heat $\dot{Q}_H$.

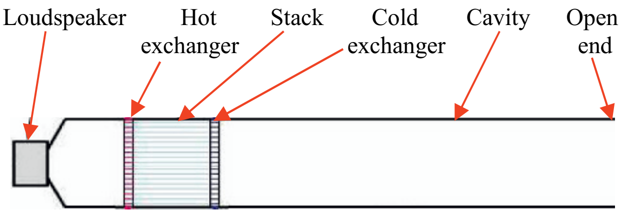


Figure 3. Schematic of thermoacoustic heat pump

It is useful that hot heat exchanger and cold heat exchanger create as low obstacles for flowing working gas inside resonator as is possible.

The most important part of any thermoacoustic device is stack, which significantly increases the efficiency of thermoacoustic devices. It is a ducts system between hot heat exchanger and cold heat exchanger inside resonator.

Ducts system can be made from parallel panes or from material with rectangular, square or hexagonal parallel holes. There can be used do not metal covered porous ceramic from car catalyst with good advantage.

Understanding the processes arising within the stack is the key for construction devices with the best possible efficiency.

2.2 Abstract from mathematical theory of thermoacoustic engine

To this time was described a lot of variants of thermoacoustic devices, but the best devices for purpose of experimental research with different working gases are probably linear thermoacoustic devices with one open end. For devices of these type are applicable some formulas, which can give better look how thermoacoustic devices works.

One of the main parameters of thermoacoustic device is frequency of resonation. This frequency f is given as:

$$f = \frac{a}{4 \cdot L} \tag{1}$$

Where a is speed of sound and L is length of resonator.

Because speed of sound in helium is bigger than speed of sound in air, and length of resonator is the same, so can be expected, that frequency of vibrations will be higher for helium.

Other important parameter is called thermal penetration depth δ_K:

$$\delta_K = \sqrt{\frac{k}{\pi \cdot \rho \cdot c_p \cdot f}} \tag{2}$$

Where k is heat conductivity of working gas, ρ is density of working gas, c_p is specific heat capacity of working gas and f is frequency of oscillations.

Parameter which is described stack construction is called hydraulic ratio, and is determined as:

$$r_h = \frac{volume\ of\ stack\ canal}{surface\ of\ stack\ canal} \tag{3}$$

From these two parameters above is possible made important indicator of stack quality in term of efficiency. This parameter is called Lautrec number:

$$N_L = \frac{r_h}{\delta_K} \tag{2}$$

Stack which have Lautrec number > 1 is called stack, stack which have Lautrec number < 1 is called regenerator. If Lautrec number ≈ 1, then is possible achieve the best efficiency.

The basic parameters, which were used for computing, are in Table 1.

Table 2. Basic parameters of working gases and stack.

		Air	Helium
Length	L (m)	0,18	
Speed of sound	a ($m \cdot s^{-1}$)	340	970
Thermal conductivity	k ($W \cdot m^{-1} \cdot K^{-1}$)	0.0262	0.1513
Density	ρ ($kg \cdot m^{-3}$)	1.275	0.176
Specific heat capacity	c_p ($J \cdot kg^{-1} \cdot K^{-1}$)	1.,01E+03	5.19E+03
Frequency	f (Hz)	500	1250
Hydraulic ratio	r_h (m)	0.0025	
Lautrec number	N_L (1)	2.04	1.23

3 Device construction and measurement setup

3.1 Device construction

For main part of experimental thermoacoustic engine was used a test-glass with length roughly 180 mm and inside diameter 15 mm.

As stack was used an unmetallized ceramics, with square cells with dimensions roughly 1 x 1 mm, which is most often used as semi-finished product in car catalysator production. This ceramics was cut up to length 25 mm and diameter necessary for putting stack inside cavity.

For heating was used resistance wire spiral, which was attached to laboratory power source.

The last part of thermoacoustic engine was balloon, which separates working gas from surrounding atmosphere. This solution allowed made thermoacoustic engine with one opened end and another working gas inside.

The overpressure of working gas produced with balloon (compliance volume) is about 3 kPa [6], this value is expected as insignificant.

Built-up device is shown at Figure 4.

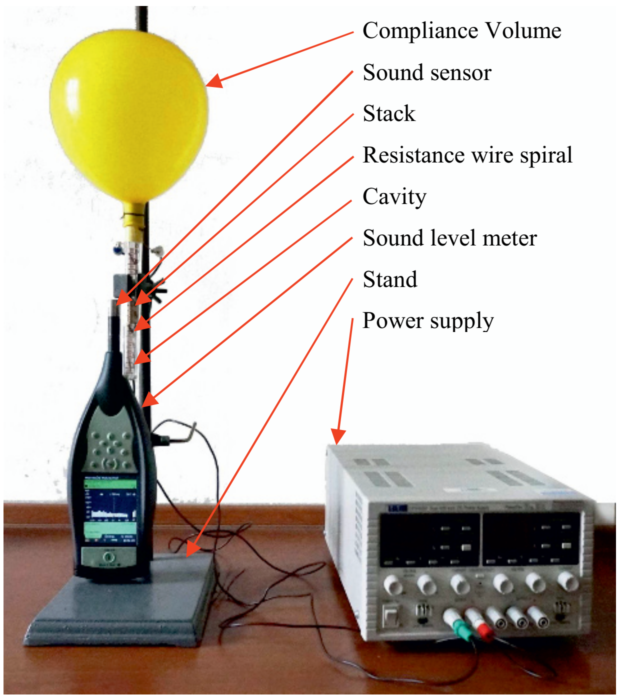


Figure 1. Scheme of thermoacoustic device

3.2 Measurement setup

During measurement was device wired in to stand by force of clamps.

For determination of main frequency of thermoacoustic engine was used a handheld sound level meter Brüel & Kjær type 2250. Sensor of sound of sound level meter was in measurement both of working gases in the same place, because it was wired in with stand. This means the same height, distance and angles.

For power supply was used direct-current power source TTi CPX400d. This power source makes possible set current to tenths of ampers and tension to hundredths of volts.

For device helium filling was device rotate upside down. To open end of device was mounted auxiliary balloon filled with helium. After few seconds after connection was air from cavity at bottom of mounted balloon. Consequently was auxiliary balloon replaced with new balloon, which was completely filled with helium. After this operation was device second time rotated upside down. This procedure was proven, and quantity of remaining air in device was insignificant.

For values recording was used camera.

4 Results

For both of measurements was used the same input current for resistance wire spiral. Value of current was kept at two amperes. During air measurement was tension about 17.8 Volts and during helium measurement was tension about 17.4 Volts.

This implies that for air measurement was used power input 35.6 Watts and for helium measurement was used power input 34.8 Watts.

During both measurements was made couple of pictures. These pictures are not synchronised with start of device so that intervals between single pictures are not exactly the same in both measurements. But those intervals are not so much different.

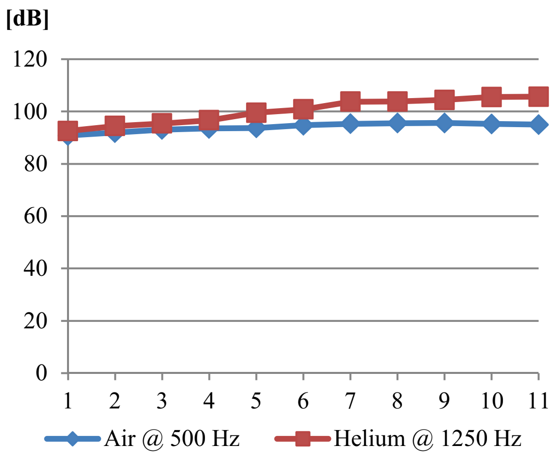
Values from took pictures was ordered in table. Sample of this table with assortment values of sound intensity is shown in Table 2.

Table 2. Sound intensity.

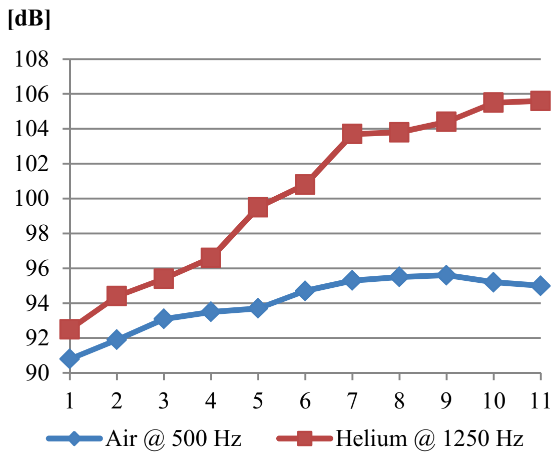
#	Air @ 500 Hz	Helium @ 1250 Hz
1	90.8	92.5
2	91.9	94.4
3	93.1	95.4
4	93.5	96.6
5	93.7	99.5
6	94.7	100.8
7	95.3	103.7
8	95.5	103.8
9	95.6	104.4

For better clearness are the same data visualised in Graph 1. Detail of these values is shown in Graph 2.

Graph 1. Intensity of sound



Graph 2. Detail of intensity of sound



Average value of intensity of sound was determined for device with air as working gas roughly 94 dB and for device with helium as working gas roughly 100 dB.

5 Conclusions

From available values results, that helium works at higher frequency than air, as was expected. Measured frequencies of working gases were the same as rated from empirical formula.

For air it was 500 Hz and for helium it was 1250 Hz.

It was expected, that device with air and helium will operate with the same power input, but during measurement was proven, that device with air has power input 35.6 watts and device with helium has power input 34.8 watts. So helium filled device has during measurement lower power consumption than air filled device.

With regard to theory was expected higher sound intensity for helium filled device than for air filled device. This presumption was confirmed, because average sound intensity of helium filled device was at 6 dB higher, than device with, which was used air as working gas.

It is evident, that helium is better working gas for thermoacoustic devices, than air. But in this research are a lot of other parameters, which can be evaluated.

6 Acknowledgements

The authors would like to thank the Grant Agency of Czech Republic GACR (project no. P101/11/J019).

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