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Research Paper

Influence of Working Conditions on Parameters of Thermoacoustic Engine with Travelling Wave

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Thermoacoustic converters are devices for direct conversion of acoustic energy into thermal energy in the form of temperature difference, or vice versa – for converting thermal energy into an acoustic wave. In the first case, the device is called a thermoacoustic heat pump, in the second – thermoacoustic engine. Thermoacoustic devices can use (or produce) a standing or travelling acoustic wave. This paper describes the construction and properties of a single-stage thermoacoustic engine with a travelling wave. This kind of engine works using the Stirling cycle. It uses gas as a working medium and does not contain any moving parts. The main component of the engine is a regenerator equipped with two heat exchangers. Most commonly, a porous material or a set of metal grids is used as a regenerator. An acoustic wave is created as a result of the temperature difference between a cold and a hot heat exchanger. The influence of working gas, and such parameters as static pressure and temperature at heat exchanger on the thermoacoustic properties of the engine, primarily its efficiency, was investigated. The achieved efficiency was up to 1.4% for air as the working medium, which coincides with the values obtained in other laboratories. The efficiency for argon as working gas is equal to 0.9%.

Keywords: thermoacoustics; thermoacoustic engine; travelling wave.

1. Introduction

The thermoacoustic effect is known for a long time. The first, who observed this were the glass blowers. They noticed that the heated pipes used for blowing glass are making sounds. In 1777, B. Higgins observed that putting a flame over a tube with open ends creates an audible sound. Another example described is the Rijke tube (1859), in which a heated metal placed in the lower part of a tube with open ends caused strong oscillations of the gas molecules. The tube generates sound only in a vertical position. The Rijke pipe with one closed end can also generate sound, provided that the closed end is heated. This phenomenon was observed by the German physicist Sondhauss. Currently, the Sondhauss tube is considered the first thermoacoustic engine. In later times it was found that the phenomena described above are reversible, meaning that heat can be generated using acoustic vibrations. Such a device is called a thermoacoustic heat pump. This phenomenon was described in the 1890s by Rayleigh (Rayleigh, 1878).

After a long period of stagnation in the study of thermoacoustic phenomena and devices, there is now a revival in this field. The advantage of these devices is the lack of moving parts, which distinguishes them from conventional heat engines. This increases the lifespan and reliability of thermoacoustic devices.

A thermoacoustic device in the simplest version consists of a regenerator and an acoustic resonator. In the regenerator, heat is exchanged between vibrating particles of the working gas and the porous structure made, e.g., in the form of a metal mesh or a sound-absorbing material. As a result of this exchange a cycle of thermodynamic changes commences, causing the creation of a closed circuit and work being made. At both ends of the regenerator there are heat exchangers – cold and hot, to which the heat is supplied, or from which it is received. An acoustic resonator can have open or closed ends. In both cases, an acoustic standing wave is created in the resonator, the length of which can be, depending on the conditions at both ends, two or four times the length of the tube. Such devices are called devices with a standing wave. Presently, devices with a travelling wave are way more significant. To achieve a travelling wave without reflections the resonator loops itself. In this case, the length of the acoustic wave is equal to the length of the tube.

2. Classification of thermoacoustics devices

As mentioned above, thermoacoustic devices can be classified based on the type of work (engines, heat pumps), regenerator material used, and the type of acoustic wave (standing wave and travelling wave). According to Garrett (Garrett, 2003; Organ, 1992), thermoacoustic devices can be divided as follows:

- heat pumps with a travelling wave,
- heat pumps with a standing wave,
- engines with a travelling wave,
- engines with a standing wave.

In devices with a standing wave there is a phase difference between the acoustic pressure p and the acoustic velocity v (Dobrucki, 2007). At full reflection, for an ideal standing wave, the difference is $\pi/2$. Thermoacoustic devices with standing waves work approximately based on the Brayton-Joule cycle and achieve efficiency up to 20%.

For flat travelling waves acoustic pressure and acoustic velocity are in phase. A travelling wave allows for the implementation of the Stirling cycle, which in case of a perfect heat conversion, achieves the Carnot efficiency. High efficiency of these devices results in more attention given to them and a big emphasis given to their development (Ruziewicz, Lamperski, 2015; Ruziewicz, Zimnowłodzki, 2014). The researcher, who discovered that travelling waves were more suitable in thermoacoustic processes because of their efficiency, was Peter Ceperley (Ceperley, 1979; Kruk, 2013). In thermoacoustic devices with a travelling wave gas, during the passage of the wave through the regenerator undergoes a cycle of isothermal compression, isochoric heating, isothermal expansion and finally isochoric cooling, analogous to the cycles occurring in a conventional Stirling engine. For this cycle to occur, there must be a perfect thermal contact between the gas and the regenerator material. This depends on the hydraulic radius and the thermal penetration depth. The hydraulic radius r_h is defined as the ratio of the surface area of a single pore to its circumference, and the thermal penetration depth, which characterizes the heat exchange between the oscillating particles of the working gas and the porous material, is given by:

$$\delta_k = \sqrt{\frac{2K}{\omega \rho c_p}}, \tag{1}$$

where K – thermal conductivity, W/(m·K), ω – angular frequency of the acoustic wave, rad/s, ρ – gas density, kg/m^3, c_p – specific heat at constant pressure, J/(kg·K) (Table 1).

Table 1. Thermal parameters of the working gases.

Parameters	Air	Argon
Specific heat	0.718	0.3122
Thermal conductivity	26.20	17.90

To ensure perfect thermal contact between the gas and the regenerator material, the hydraulic radius must be much smaller than the thermal penetration depth:

$$r_h \ll \delta_k. \tag{2}$$

The gas undergoes reversible transformations – it compresses with increasing temperature and expands with its decrease. As a result, a constant heat exchange between gas and material is maintained, which takes place at a negligible small difference in temperature, resulting in a slight increase in entropy. During compression and expansion (step 1 and 3), the temperature remains constant (Swift, 1988; Abduljalil, 2012).

If the thermal contact is insufficient ($r_h \simeq \delta_\kappa$) the device using the travelling wave works inefficiently. Heating and cooling are delayed. Thermodynamic transformations are not reversible and do not coincide with the Carnot cycle. During the first phase of the cycle, the particle is compressed, but it does not absorb heat perfectly.

Phases of the thermodynamic cycle for both cases are presented in Figs 1 and 2.

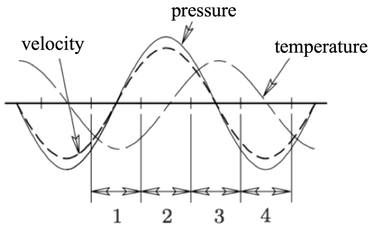


Fig. 1. Waveforms of pressure, acoustic velocity, and temperature as function of time for a travelling wave and $r_h \ll \delta_k$.

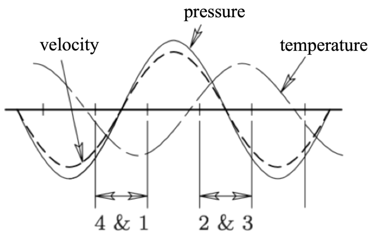


Fig. 2. Waveforms of pressure, acoustic velocity, and temperature as function of time for a travelling wave and $r_h \simeq \delta_k$.

If the wave propagates towards the temperature gradient, the system operates as a thermoacoustic engine, if the propagation direction is opposite to the gradient, the system acts as a heat pump.

The side effect of using a small hydraulic radius of the regenerator is a significant increase in viscosity-induced losses. For this reason, thermoacoustic devices with a travelling wave should be designed so that the acoustic impedance in the regenerator module was as large as possible (de Blok, 2010; 2012; Zhibin, Jaworski, 2010).

3. Design the thermoacoustic engine with a travelling wave

3.1. Construction of the engine

The thermoacoustic engine generates acoustic energy from the supplied heat. The most important element of the engine is the regenerator section, along which there is a temperature difference caused by the supply of heat to the hot exchanger and heat pickup in the cold exchanger on the other side.

In order for the thermoacoustic engine to work according to the Stirling thermodynamic cycle, it is necessary to meet the propagation conditions of the travelling wave. One of the solutions is to construct a waveguide of a thermoacoustic engine as a looped tube (Ruziewicz *et al.*, 2018). The length of the waveguide is then equal to the wavelength generated by the device (Fig. 3) (Abduljalil *et al.*, 2011). Thanks to this geometry, an acoustic wave will circulate in the loop, which will be amplified by the regenerator module (Kruk, Ruziewicz, 2016). Air and argon at various pressures were used as working gases.

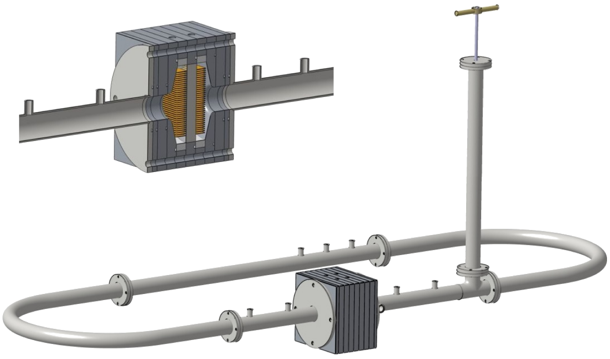


Fig. 3. A 3D model of a thermoacoustic engine with a travelling wave.

To reduce the viscosity-induced losses in the regenerator, the regenerator cross-section area should be increased. Thanks to this, the acoustic velocity will decrease, on which the viscosity losses directly depend. To avoid reflections of the acoustic wave on the discontinuity in the regenerator module there is a smooth transition from the cross-section of 43 mm to 136 mm (Fig. 4). The diameter change occurs in a ring with a cone-shaped cross-section that is 20 mm in length (Kruk, Dobrucki, 2017).

In the system there is also a stub pipe closed at one end, thus acting as an acoustic susceptibility element (Kruk, 2012). Its task is to match the wave

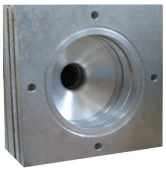


Fig. 4. Cross-section increase in the regenerator module.

impedance in the regenerator to reduce the wave reflection effect. This short-closed stub is a compliance type effect. According to Ruziewicz *et al.* (2018), its option position is in $^3/_4\,\lambda$ from regenerator. The waveguide length of the thermoacoustic engine is 5.73 m. For devices with traveling waves the length of a tube is equal to the wavelength of generated acoustic wave. Then, frequency of the engine operation is given by formula:

$$F = \frac{c}{\lambda}, \tag{3}$$

where c is the speed of the acoustic wave. This speed is equal to 347 m/s for air and 323 m/s for argon at 27°C, hence the frequency of the engine operation is 60.5 Hz, when air is the working gas and 56.4 Hz, when argon is the working gas.

The device's waveguide and stub were constructed using steel pipes with an outer diameter of 48 mm and a wall thickness of 2 mm. The pipes were connected with special steel flanges with a thickness of 10 mm and sealed with O-rings. The length of the stub pipe can be adjusted using a screw terminated with a sealed piston passing through the threaded hole in the cover. The combination of the regenerator module and the waveguide was made using flanges with a larger diameter.

3.2. Regenerator

The regenerator module (Fig. 5) is made of aluminium rings with pressed holes that connect the waveguide loop to form an acoustic chamber. This area hosts the heat exchangers and the regenerator itself. On the left side of the rings, the grinds for rubber O-rings were made to ensure adequate tightness for static pressures of up to 10 bars.

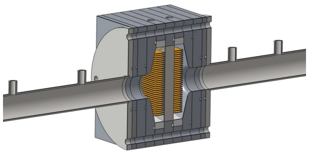


Fig. 5. The regenerator module (core) of the thermoacoustic engine.

Holes with a smaller diameter (⌀ 43 mm) are an extension of the waveguide, while those with a larger diameter (⌀ 136 mm) form the side walls of the acoustic chamber. The use of two types of rings allows for the change the configuration of heat exchangers and regenerator (e.g. offsetting the exchangers from the regenerator material by a few centimetres). For the regenerator and the heat exchangers, rings with an inner diameter of 136 mm and a thickness of 20 mm are used.

A stack of 2 cm thick steel meshes was used as the regenerator material. The construction of a single grid is shown in Fig. 6

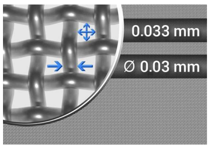


Fig. 6. Steel mesh used for the regenerator: surface area 0.033 mm^2, diameter 0.03 mm.

3.3. Thermal isolation

In order to ensure adequate thermal insulation and to limit heat transfer from the hot heat exchanger (in which the temperature reaches values up to 700°C), a ceramic ring was used for the waveguide. Modern thermal insulation (ceramic fibre modules) have better thermal parameters than traditional materials such as mineral wool. Thermal conductivity K of thermal insulation made of ceramic fibres have values from 0.018 to 0.040 W/(m·K) (www.europolit.pl, 2019). The designed solution is shown in Fig. 7.

O-rings sealing the engine core were replaced with novamicaTHERMEX materials. It is a technologically advanced seal plate that maintains stability at extremely high temperatures. It is made of phlogopite (a type of mica), and has excellent resistance to high temperatures in the range up to 1000°C. Thanks to a stainless steel insert, novamicaTHERMEX is perfectly suitable for processing, ensuring perfect tightness in high temperature conditions for a long time.

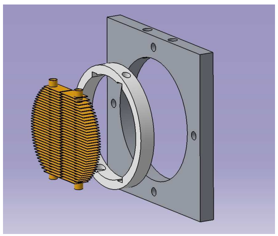


Fig. 7. Thermal isolation – hot heat exchanger.

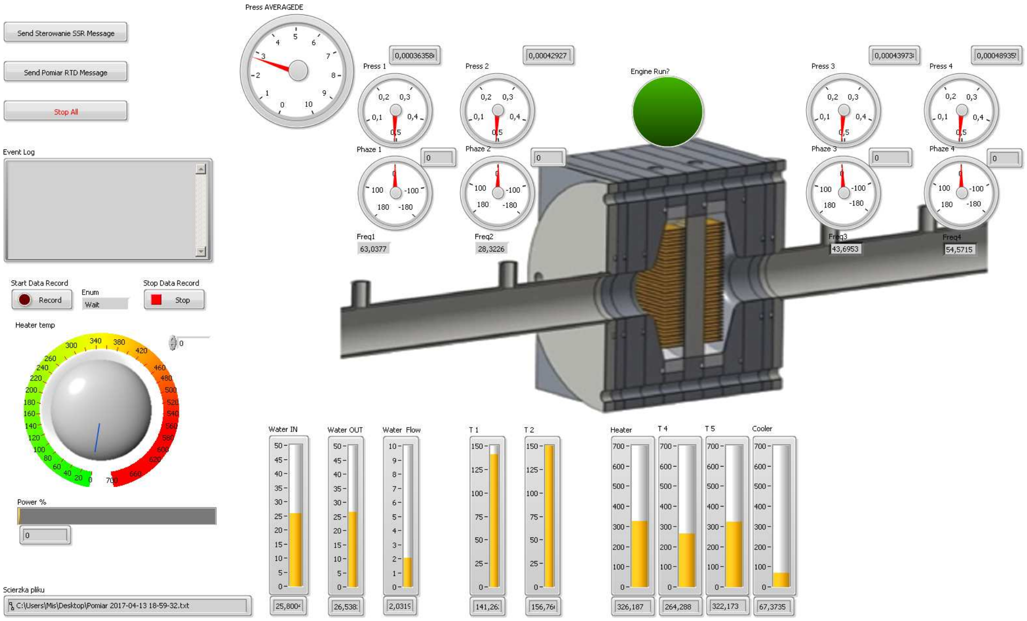
3.4. Heat exchangers

A heat exchanger is a piece of equipment built for efficient heat transfer from one medium to another. As described thermoacoustic engine heat exchangers are used to supply and remove heat from the system. Heat exchangers are made of copper, which has a very good thermal conductivity characteristic, necessary for the efficient operation of the entire device.

4. Measurements of the thermoacoustic engine

4.1. System of measurement

For the research purposes, it is necessary to monitor a lot of data to determine the characteristics of operation of the engine with a travelling wave. Due to this, the system contained: 4 pressure sensors, 9 temperature sensors, 1 flow sensor.



Press 1: 0,00036358
Press 2: 0,00042927
Press 3: 0,00043973
Press 4: 0,00048935
Phaze 1: 0
Phaze 2: 0
Phaze 3: 0
Phaze 4: 0
Freq1: 63,0377
Freq2: 28,3226
Freq3: 43,6953
Freq4: 54,5715
Enum: Wait
Heater temp: 0
Power %: 0
Scierzka pliku: C:\Users\Mis\Desktop\Pomiar 2017-04-13 18-59-32.txt
Water IN: 25,800
Water OUT: 26,538
Water Flow: 2,0319
T 1: 141,26
T 2: 156,76
Heater: 326,187
T 4: 264,288
T 5: 322,173
Cooler: 67,3735

Fig. 8. The control panel of the thermoacoustic engine (the panel shows the location of the sensors: pressure, phase and temperature).

Collecting and controlling such a large amount of data forces that the whole measurement system be fully automated. Engine operation is controlled using a program created in the LabView graphic environment. The control panel (Fig. 8) indicates the location of all sensors. Due to the very large number of processed data, the results were saved in real time to a text file, which was later analysed.

During the test engine start-up a significant heat transfer from the hot heat exchanger towards the waveguide and measuring systems was noticed. In order to minimize the risk of damaging the pressure sensors and ensuring correct data reading, a second radiator with a spiral structure was installed and mounted directly behind the regenerator module on the waveguide (Fig. 9).

Fig. 9. Additional radiator.

4.2. Measurements

The only material used in the regenerator for which positive results were obtained was a steel mesh. The tests were carried out for a stack of 2 cm thick meshes (Fig. 6) and two working gases, i.e. air and argon for static pressures in the range of 1–8 bars.

4.2.1. Research results for air as a working gas

The physical properties of the working gas have a large impact on the operation of thermoacoustic devices. Constructed engine with air as a working gas works at a frequency of 60.5 Hz.

Table 2 presents the results of measurements of temperatures on the cold and hot heat exchanger and their difference at the start-up of the thermoacoustic engine.

Table 2. Temperature values in a thermoacoustic engine at start-up for air as an operating medium.

Working gas – air			
Temperature difference [°C]	T_H [°C]	T_C [°C]	P_s [bar]
447.2	488.4	41.1	4.0
383.2	427.5	44.3	5.5
320.2	360.9	40.6	6.1
323.6	352.1	28.5	6.8
243.2	292.8	49.6	7.1

T_H – the temperature at the hot heat exchanger,
T_C – the temperature at the cold heat exchanger,
Ps – static pressure in the engine.

It can be observed that increasing the pressure in the waveguide requires an ever lower temperature to start the engine. This is due to better thermodynamic adjustment.

In order to verify the engine's operating conditions, a number of measurements have been made for steady conditions, i.e. operation of the device for several minutes at constant temperature on the hot heat exchanger and constant pressure in the waveguide. The program saved over 5000 results for a single measuring point. The averaged results are presented in Table 3.

Table 3. Working parameters of the engine – steady conditions.

P_s [bar]	3.9	4.0	3.9	4.9	6.0
T_H [°C]	400.1	427.7	450.0	354.2	357.1
P SSR [%]	60.1	75.6	79.9	48.2	52.8
$\dot{Q}_h$ [W]	841.1	1058.0	1118.5	675.3	739.8
$\dot{Q}_c$ [W]	352.6	208.7	457.6	296.1	287.3
$\dot{Q}$ [W]	488.5	849.3	660.9	379.2	452.5
η [%]	0.9	0.6	0.9	1.2	1.4
P_A [W]	4.5	5.0	6.1	4.5	6.5

P_s – static pressure of the working gas in bar, P SSR – percentage share of SSR (Solid State Relay) relays work.

Supplied power is given by:

$$\dot{Q} = \dot{Q}_h - \dot{Q}_c \tag{4}$$

$\dot{Q}_h$ is supplied power measured at the hot heat exchanger as:

$$\dot{Q}_h = 1400 \cdot P\ \text{SSR}\ [\text{W}], \tag{5}$$

where 1400 W power of the heater, $\dot{Q}_c$ – thermal power at the cold exchanger.

Acoustic power is given by formula:

$$P_A = \frac{p^2}{Z}, \tag{6}$$

where p – RMS of the acoustic pressure [Pa], Z – acoustic impedance of the waveguide [kg/(m$^4 \cdot$s)].

Energy conversion efficiency of the thermoacoustic engine equals:

$$\eta = \frac{P_A}{\dot{Q}} \cdot 100\%. \tag{7}$$

Considering the engine operation for static pressure in the waveguide of around 4 bars, it can be observed that by increasing the supplied thermal energy (i.e. a higher temperature on the hot heat exchanger) an even higher value of the generated acoustic power is obtained. At a constant temperature value on the hot heat exchanger and increased static pressure in the waveguide, the obtained acoustic power value also increases. For a temperature of 350°C on a hot heat exchanger and an increase in pressure from 5 to 6 bars, the acoustic power increased from 4.5 to 6 W. This is due to the thermal penetration depth.

Figure 10 shows the dependence of the sound pressure level in the waveguide from the static pressure for a constant temperature on the hot heat exchanger of 430°C. It is possible to observe the engine operation in the full range of the tested static pressure. The curve shown in the figure was obtained by gradually reducing the pressure in the waveguide, because thermoacoustic engines require much more energy to start than to later work.

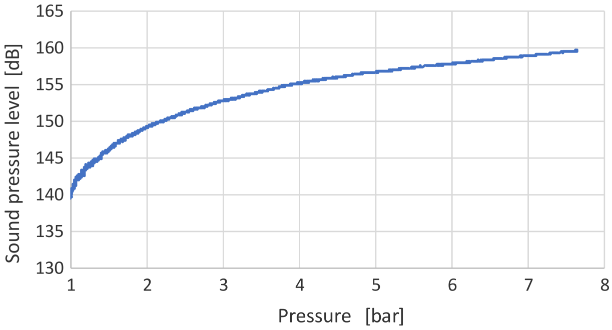


Fig. 10. The dependence of the sound pressure level in the waveguide on the static pressure for a constant temperature on the hot heat exchanger of 430°C.

Figure 11 shows the dependence of the sound pressure level on the temperature of the hot heat exchanger for a constant pressure in the waveguide of 4 bars. It can be observed that by increasing the temperature on the hot heat exchanger by 90°C, has been obtained increase in the acoustic pressure generated by almost 7 dB SPL.

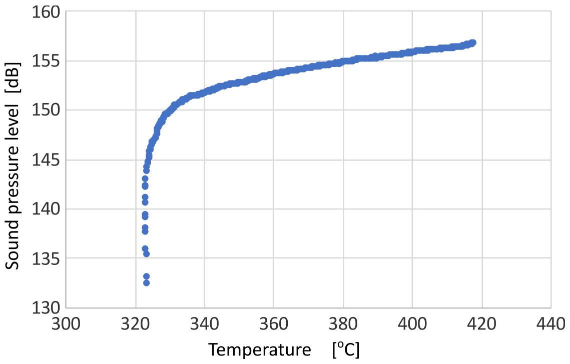


Fig. 11. Value of acoustic pressure depending on the temperature on the hot heat exchanger for static pressure in the waveguide of 4 bars – working medium air.

4.2.2. Research results for argon as a working gas

The constructed engine with argon as a working gas operates at the frequency of 56.4 Hz. As a result of different thermoacoustic properties of argon, a higher value of supplied heat is required to start the engine than in the case of air. The values of temperatures needed to start the engine are shown in the table below. As with air, it can be observed that increasing the pressure in the waveguide requires a gradually lower temperature to start the engine, which results from a better thermodynamic correlation.

Table 4. Temperature values in a thermoacoustic engine at start-up – operating medium argon.

Working gas – argon			
Temperature difference [°C]	T_H [°C]	T_C [°C]	P_s [bar]
406.4	434.2	27.8	8.7
434.7	470.5	35.8	8.2
497.8	551.0	53.2	5.8
465.0	514.1	49.1	5.7

Figure 12 shows the value of the sound pressure level depending on the temperature on the hot heat exchanger for a constant static pressure in the waveguide of 6.6 bar. The largest value of the sound pressure level is for the temperature on the hot heat exchanger of 476°C.

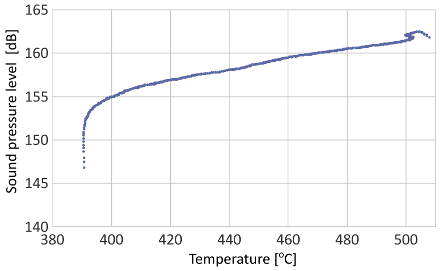


Fig. 12. The dependence of the sound pressure level on the temperature on the hot heat exchanger for a constant pressure in the waveguide of 6.6 bar – working medium argon.

4.3. Discussion

Table 5 lists engine start-up parameters at a pressure of 6 bars. It can be noticed that despite the generation of more acoustic power using argon as a working

Table 5. Engine operating parameters – steady conditions – pressure of 6 bars.

Working gas	Argon	Air
P_s [bar]	5.8	6.0
T_H[°C]	443.4	357.1
P SSR [%]	71.2	52.8
$\dot{Q}_h$ [W]	997.2	739.8
$\dot{Q}_c$ [W]	145.3	287.3
$\dot{Q}$ [W]	852.0	452.5
η [%]	0.9	1.4
P_A [W]	8.1	6.5

gas, the efficiency of the engine is almost 40% lower compared to air. This is due to the higher engine starting temperature of 90°C.

A similar relation can be observed by analysing the temperature values needed to start the thermoacoustic engine in Table 6.

Table 6. Engine operating parameters – steady conditions.

Working gas	Argon	Air
T_H [°C]	569	361
T_C[°C]	33	41
ΔT [°C]	535.7	320
P_s [bar]	5.8	6.1

5. Conclusions

The paper presents a constructed thermoacoustic device with a running wave and its influence on the acoustic parameters, mainly energy efficiency, was examined. Two working gases were used: compressed air and argon. These gases have similar values of sound velocity and specific acoustic resistance, but differ in the value of thermal conductivity and specific heat. As expected, the operating frequency of a fixed length device filled with these gases varies little. The hydraulic radius and thermal penetration depth has the greatest influence on efficiency. For this reason, the energy efficiency for argon is much lower than for air. Also the starting conditions for argon are much worse than for air. In order to improve operating conditions and efficiency for argon, it is necessary to change the design parameters of the device (primarily the regenerator).

The influence of temperature and static pressure on the start-up parameters of the device and on the efficiency and sound pressure in fixed operating conditions was also examined. The steady state sound pressure level is 147 dB for air and 157 dB for argon. After starting the engine, as the temperature rises, the pressure rises to 156 dB for air and 161 dB for argon. These values are very difficult to achieve for other acoustic signal generators.

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