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Performance Evaluation of Ceramic Substrates for Cooling Applications in Thermo-Acoustic Refrigerators

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Abstract

Thermo-acoustic refrigerators have recently drawn more attentions because of its eco-friendlier potential to address the current environmental issues resulting from the use of traditional vapour compression refrigerators. This paper aims at evaluating different selected ceramic substrates, with square pores, from the point of view of their performance as stack materials in the design of thermo-acoustic standing wave refrigerators. A 465 mm standing wave thermo-acoustic refrigerator was designed using numerical approximation provided by a modeling code called DELTAEC (Design Environment for Low-amplitude Thermo-Acoustic Energy Conversion). The design developed focuses in particular, on the effects of different ceramic substrate configurations (diameter, length, porosity and position) on the performance of the device. Meaningful comparison on the effect of the ceramic substrates configuration is provided in order to assess the performance of the device. Guidance on the identification and the selection of the best geometrical configurations of ceramic substrates are the main contributions of this work.

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Keywords: Thermo-acoustic; DeltaEc; ceramic substrate; refrigerator.

1. Introduction

The evolution of thermo-acoustic devices has come a long way. Although this technology is still at the developmental stage, current researches focus on the designing of practical devices for domestic and industrial

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applications. These researches are being conducted to develop, improve and analyse the performance of the thermo-acoustic devices [1]. The expansion of earth population has become greater for the planet to sustain its consumption, nor the environment to support the pollution. The design of the thermo-acoustic devices promises a good contribution to reducing air pollution. In this study, a simulation code is used to design a simple standing wave thermo-acoustic refrigerator. This device uses sound oscillating in the small channels to produce cooling power. It is a potential alternative to the conventional refrigerators. It can be driven by wasted heat, has no toxic coolants, and does not require the use of lubricants. Its simplicity means low manufacturing and low maintenance costs. Thermo-acoustic refrigerator (TAR), also called heat pump, uses acoustic energy to generate cooling effect. It consists of a hermetically sealed tube (resonator), a porous material (stack) where the temperature gradient is created, two heat exchangers used to absorb and dissipate the heat energy, and a speaker for acoustic generation.

In Fig. 1, an illustration of the working principle of TAR is provided. A sound creates oscillations of heat between particle of gas and the channel wall of the stack (Fig. 2). The combination of these oscillations and the heat transfer resulting from it, produces the thermo-acoustic effect. Details description of the working of TAR can be found in Ref [2].

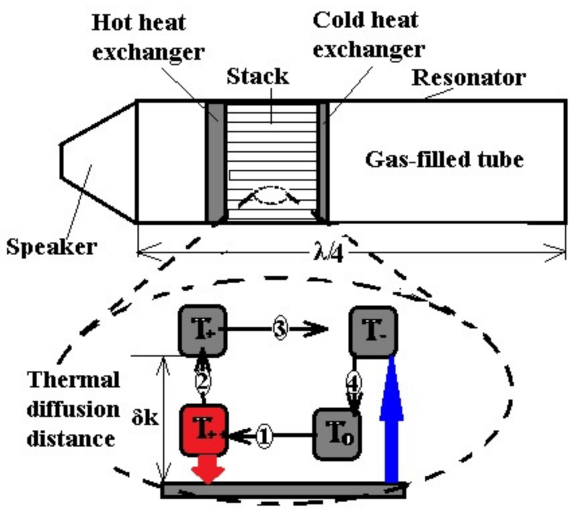

Fig. 1. Thermo-acoustic refrigerator and thermo-acoustic cycle

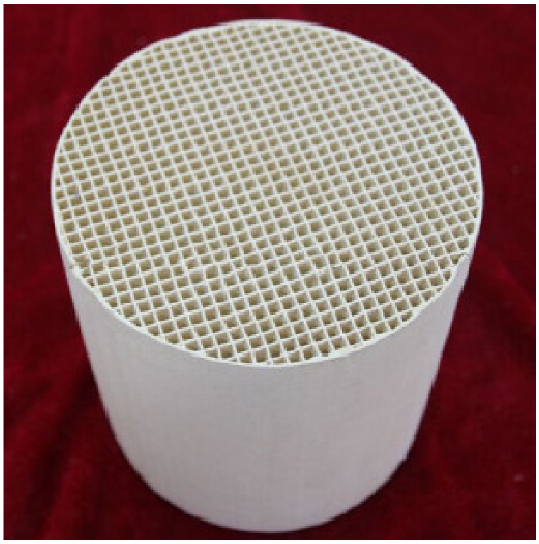

Fig. 2. Stack

2. Material choice and motivation

The stacks were made of ceramic substrate materials with regular square channels. Their production technology involves: mixing the raw materials, kneading, forming, firing, gridding and polishing the final product [3]. The ceramic substrate is one of the preferred materials, it is also used as a catalytic converter in exhaust systems. When compared to other materials, it offers many advantages, including, low cost, high mechanical strength at high temperature, thermal stability, uniform porosity, availability, low thermal conductivity, high melting point and high heat capacity [4]. Although Mylar stack produces also a higher performance, it is relatively difficult to fabricate, especially in order to maintain uniform spacing within the stack. Many researches have highlighted that the performance of thermo-acoustic devices depend on the material and the geometrical configuration of the stack [5,6]. This paper intends to demonstrate how the geometrical configuration of the stack, namely the diameter (*d*), the length (*Ls*) and the stack position (*Xs*), affects the performance of the device. We have chosen to study the influence of these parameters on the performance of a standing wave thermo-acoustic refrigerator.

3. Identification of main parameters

There are many parameters surrounding a thermo-acoustic device and contributing to its performance. These parameters may be separated into groups [6]:

- Operating parameters: Mean temperature (*Tm*), dynamic Pressure (*Po*), frequency (*f*) and mean pressure (*Pm*);
- Gas parameters: Dynamic viscosity (μ), thermal conductivity (*K*), sound velocity (*a*), specific heat (γ), density (ρ);
- Stack parameters: stack length (*Ls*), plates spacing (*2yo*), stack position (*Xs*), porosity (ϕ), plates thickness (*2l*), cross section (*A*), thermal conductivity (*Ks*); density (ρ), specific heats (*Cs*).

The following assumptions were made to define the working condition of the device:

- The length of the resonator (*Ls*) was set to be 465 mm. For a standing wave thermo-acoustic device, the resonator length is either a half wavelength (λ/2) or or a quarter wavelength (λ/4);
- The frequency obtained with the quarter wavelength assumption was evaluated to be ± 368.8 Hz.

The following tables depict the summary of parameters used for the simulation.

Table 1. Operating and gas parameters

Operating & gas Parameters	***Pm (bars)***	***Po (bars)***	***f Hz***	***Tm K***	***μair20º Kg/ms***	***Kair20º W/(mk)***	***aair20º m/s***	***γair20º Kj/(KgK)***	***ρair20º Kg/m³***
Values	10	0.3 and 0.15	± 368.8 Guessed	± 300 Guessed	18.2	0.0257	343	1.005	1.205

Table 2. Geometrical parameters

Geometrical Parameters	***Ds mm***	***Ls mm***	***Xs mm***	***ϕ CPSI***	***HX thickness (mm) Ambient/Cold***	***L Resonator mm***
Values (range)	40-150	5-70	30-100	300 and 600	10/5	465

4. Illustration of the simulation procedure

The parameters defined previously were used as input parameters in the DELTAEC models;

- The influence of the diameter on the performance of the TAR was investigated for two specific stack pore density (300 CPSI and 600 CPSI) and at two selected drive ratio (*DR* = 0.03 and *DR* = 0.015). The drive ratio is the ratio of dynamic and mean pressures (Po/Pm). The best diameter was identified and the optimal drive ratio was adopted.
- The influence of the length on the performance of the TAR was investigated for the two stack pore density as initially. In addition, the optimal diameter was sought based on the results obtained previously. The best length and diameter were identified;
- The influence of the stack position on the performance of the TAR was investigated for the two stack pore density. In addition, the optimal stack position, diameter and length were sought and identified;

The results obtained with the two stack pore density were compared.

5. DeltaEc model design, analysis and results

The DeltaEc (Design Environment for Low amplitude Thermo-acoustic Energy Conversion) is a design program that numerically integrates wave equations in a gas according to patterns defined by the user as a sequence of segments such as duct, stack, heat exchangers (Hx) as shown in Fig. 3. This software is increasingly used for its ability to update dependent values after every alteration, to achieve design of equipments at desired performances, to integrate differential equations for each segment with pressures and other variables, and to display results using user interface, built-in graphics displays, or a spreadsheet. It is readily available from the Los Alamos National Laboratory website [7].

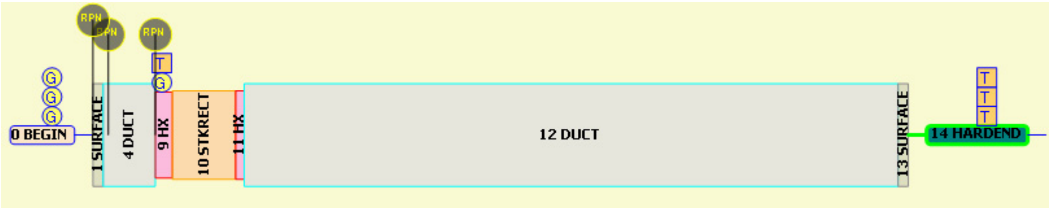

Fig. 3. Pictorial representation of DeltaEc refrigerator

The simulation has been conducted varying the diameter, length and stack center position on two stack pore density , to find the maximum relative coefficient of performance (COPr), defined as the ratio of the coefficient of performance (COP) and the theoretical maximum coefficient of performance named Carnot (COPCarnot).

$$COP = \frac{Q}{W} \tag{1}$$

$$COP_{Carnot} = \frac{Th - Tc}{Tc} \tag{2}$$

$$CO\,Pr = \frac{COP}{COP_{Carnot}} \tag{3}$$

Where Q is the gross cooling, W is the acoustic power, Th and Tc are temperatures at the hot and cold heat exchangers respectively. These equations have been incorporated into the DeltaEc program by means of a reverse polish notation (RPN) to perform algebraic calculations.

Dry air has been used as gas, 4 parameters (The frequency, the temperature at BEGIN, the flow and the heat flowing at the ambient side) have been used as “GUESSES” and 4 others (The temperature of the solid at the ambient side, the inverse of the normalised impedance and the total energy flow) as “TARGETS”.

5.1. Variation of stack diameter

Table 3 gives the input parameters used to study the influence of the diameter on the performance of TAR.

Table 3. DeltaEc input parameters for stack diameter variation

Cell density CPSI	Diameter (mm)	Length (mm)	Center position (mm)	Drive ratio (mm)	Porosity %	Wall spacing (mm)	Plate spacing (mm)	Net heat (W)
300	50-150	40	60	0.03-0.015	74	0.19	1.28	3
600	45-140	40	60	0.03-0.015	75	0.17	1.1	3

The results showing the performance of the TAR as a function of the drive ratio for a 300 CPSI and 600 CPSI are reported in Fig. 3 and Fig. 4 respectively. The results obtained clearly portray that the highest performance of TAR is expected with a drive ratio of 0.03. The influence of the diameter on the performance of the TAR is also reported in Fig. 3 and Fig. 4. For a 300 CPSI, the 79 mm diameter stack produces the highest performance corresponding to 6.8 % at the frequency of 365.74 Hz. A maximum of 7.84% has been obtained with a 600 CPSI at the frequency of 365.39 Hz.

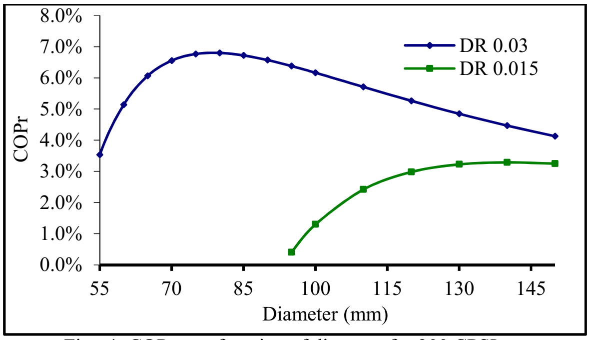

Fig. 4. COPr as a function of diameter for 300 CPSI

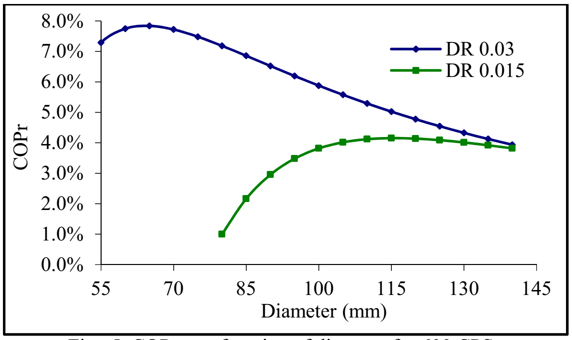

Fig. 5. COPr as a function of diameter for 600 CPS

5.2. Variation of stack length

Table 4 gives the input parameters used to study the influence of the stack length on the performance of TAR.

Table 4. DelatEc input parameters for stack length variation

Cell density CPSI	Diameter (mm)	Length (mm)	Center position (mm)	Drive ratio (mm)	Porosity %	Wall spacing (mm)	Plate spacing (mm)	Net heat (W)
300	74-84	20-50	60	0.03	74	0.19	1.28	3
600	50-80	20-70	60	0.03	70	0.17	0.87	3

The results showing the performance of the TAR as a function of the stack length for a 300 CPSI and 600 CPSI are reported in Fig. 6 and Fig. 7 respectively. The results obtained clearly portray that the highest performance of TAR is expected with a 37 mm stack. The influence of the diameter on the performance of the TAR has also been investigated. For a 300 CPSI, the 78 mm diameter produces the highest performance corresponding to 6.83 % at the frequency of 365.9 Hz. A maximum of 7.87% has been obtained with a 600 CPSI at the frequency of 365.6 Hz.

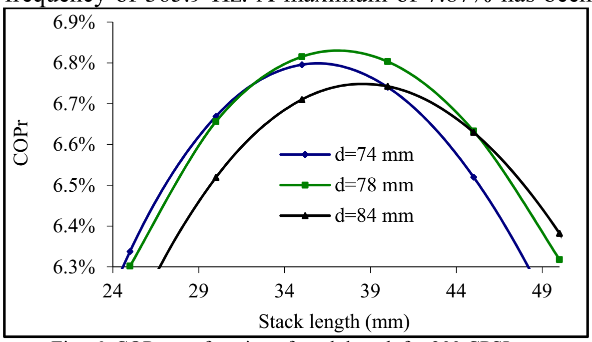

Fig. 6. COPr as a function of stack length for 300 CPSI

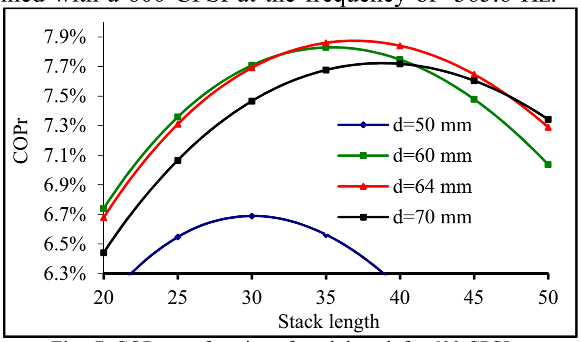

Fig. 7. COPr as a function of stack length for 600 CPSI

5.3. Variation of the stack center position

Table 5 gives the input parameters used to study the influence of the stack center position on the performance of TAR.

Table 5. DeltaEc inputs parameters for satck length variation

Cell density CPSI	Diameter (mm)	Length (mm)	Center position (mm)	Drive ratio (mm)	Porosity %	Wall spacing (mm)	Plate spacing (mm)	Net heat (W)
300	78	34-40	50-70	0.03	74	0.19	1.28	3
600	64	32-37	50-70	0.03	70	0.17	0.87	3

The results showing the performance of the TAR as a function of the stack center position for a 300 CPSI and 600 CPSI are reported in Fig. 8 and Fig. 9 respectively. The results obtained clearly portrays that the highest performance of TAR is expected with a stack located 59 mm (for the 300 CPSI) and 55 mm (for 600 CPSI) from the loudspeaker. In addition, the influence of the diameter and the stack length on the performance of the TAR have been investigated. For a 300 CPSI, the 78 mm diameter, 37 mm long stack produces the highest performance corresponding to 6.83 % at the frequency of 366.14 Hz. A maximum of 8.01% has been obtained with a 600 CPSI at the frequency of 366.9 Hz.

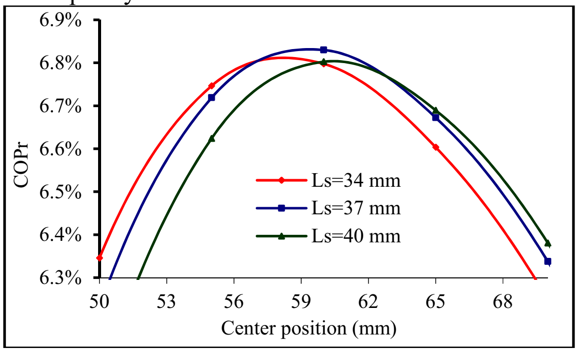

Fig. 8. COPr as a function of stack position for 300 CPSI and 78 mm diameter

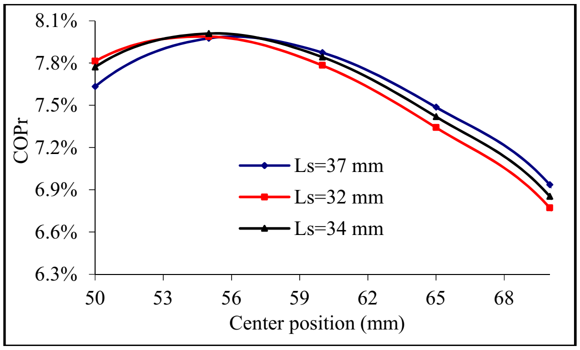

Fig. 9. COPr as a function of stack position for 600 CPSI and 64 mm diameter

6. Conclusion

The standing wave thermoacoustic refrigerator model shown in Fig. 3 has been simulated using DeltaEc software and the performance evaluated in terms of relative coefficient of performance by varying the geometrical configuration of ceramic substrates used as stack in TAR namely the diameter, the length and the position. Two drive ratio (DR = 0.03 and DR = 0.015) were investigated, and the drive ratio of 0.03 has been found performing far better than the drive ratio of 0.015, hence the former was selected for the rest of the investigation.

The following is the tabulated best values resulting from variations of diameter, length and position of ceramic substrate stacks inside a 465 mm long resonator.

Table 6. Summary of the best geometrical configuration of ceramic substrates and corresponding parameters

CPSI	Diameter (mm)	Length (mm)	Position (mm)	DR	COPr (%)	Frequency (Hz)
300	78	37	59	0.03	6.83	366.14
600	64	34	55	0.03	8.01	366.9

In conclusion, when replacing the 300 by 600 CPSI, the relative coefficient of performance increases by 1.18%.

Acknowledgment

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