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ScienceDirect

Procedia Manufacturing 7 (2016) 79 – 85

Procedia MANUFACTURING

International Conference on Sustainable Materials Processing and Manufacturing, SMPM 2017, 23-25 January 2017, Kruger National Park

Experimental investigation of ceramic substrates in standing wave thermoacoustic refrigerator

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Abstract

This work experimentally investigates the performance of ceramic substrates used as stacks in standing wave thermoacoustic coolers. Thermoacoustic technology is proposed in this study as an alternative sustainable solution to current issues with vapour compression refrigerators because of its environmentally friendlier attributes. However, the main hindrance to the expansion of this technology is its current lack of efficiency. Hence, an experimental investigation was conducted in this study. The influence of the geometrical configuration of the stack, described as the heart of the device, is investigated. The device was equipped with different selected low-cost porous materials (ceramic substrates) for performance testing and studies. Porosity, length and position of the ceramic substrates are variables that are considered in order to investigate the performance of the cooler. Eight cordierite honeycomb ceramic substrates with square cross sections and of four different lengths (26 mm, 48 mm, 70 mm and 100 mm) were considered. Five different stack positions, measured from the hot ends of the stack to the pressure antinode in increments of 100 mm, were investigated. Measurement of temperature difference at steady state was used to determine the performance of a particular configuration. Guidance on the design of this sustainable solution for refrigeration and selection of the best geometrical configuration of ceramic substrates are provided. In addition, clarity on the relation between the geometrical configurations and the frequencies of the sound wave is highlighted.

Peer-review under responsibility of the organizing committee of SMPM 2017

Keywords: Thermoacoustic,refrigeration,ceramic substrates; performance

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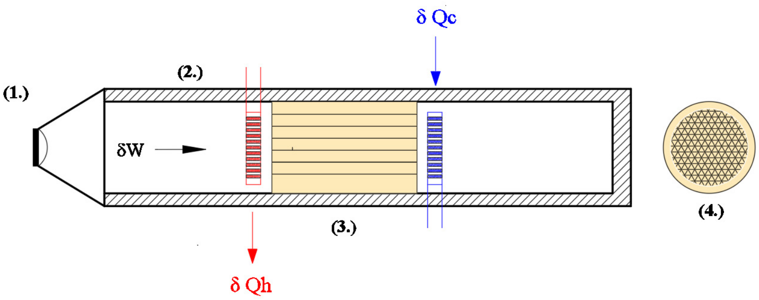
Peer-review under responsibility of the organizing committee of SMPM 2017
doi:10.1016/j.promfg.2016.12.021

Nomenclature

f	Resonant frequency	(*Hz*)	Tm	Mean temperature	(°*C*)
δk	Thermal penetration	(*mm*)	T_{hot}	Temperature at hot side of stack	(°*C*)
v	Speed of sound	(*m/s*)	T_{cold}	Temperature at cold side of stack	(°*C)*
L	Length of resonator tube (mm)	(*mm*)	ΔT	Temperature difference	(°*C)*
CPSR	Cells per square inch		Xs	Stack position from closed end	*(mm)*
Ks	Thermal conductivity of stack	(*W/mK*)	L_s	Length of stack	*(mm*)

1. Introduction

Thermoacoustics is a study that focuses on the interaction of thermodynamics and acoustics. Acoustic waves contain coupled pressure and displacement oscillations. These sound waves drive parcels of gas and interact with boundaries that cause a thermal change [1]. Thermoacoustic effect is the energy transformation of acoustic work absorbed to transport heat (thermoacoustic refrigerator TAR) or the energy conversion of the heat supplied to produce acoustic work (Thermoacoustic engine TAE) [2]. The thermoacoustic cooler converts acoustic standing waves into a temperature gradient. They consist of a resonator tube connected to loudspeaker filled with a gas medium. Inside the resonator tube, a stack and two heat exchangers can be found (see Fig. 1). The loudspeaker produces an acoustic standing wave at the fundamental frequency which interacts with a porous medium known as the stack [3]. The incentive for these systems to compete with commercial refrigerators is lack of moving parts. Furthermore, unlike the vapour compression cycle, the thermoacoustic refrigerator uses gas mediums which are environmentally friendlier than commercial refrigerants. Although these systems are simple to design, the main hindrance of the development of this technology is the efficiency and performance [4]. Therefore, further research is required.



KEY	
(1.)	SPEAKER
(2.)	RESONATOR
(3.)	STACK
(4.)	FRONT VIEW OF STACK
δW	ACOUSTIC WORK INPUT
δ Qh	HOT HEAT LOAD
δ Qc	COLD HEAT LOAD

Fig 1. Thermoacoustic Refrigerator

The ‘heart’ of a thermoacoustic system is known as the stack. This porous medium experiences maximum losses due to viscous resistance and thermal losses [5]. The stack acts as a boundary for the compression and expansion of gas. The gas follows an approximate Brayton cycle [6]. The stack material is of vital importance as the thermal conductivity and specific heat capacity influence the heat transfer performance in the system [7].

2. Stack geometry and performance of TAR

Stack length, porosity, stack position and acoustic frequency are all variables which influence the efficiency or the performance of the TAR. It is therefore a challenge to select the material and the suitable type of stack. Common material choices for stacks are ceramic catalysts, mylar, stainless steel, carbon and metallic foams. Stack types consist of parallel plates, honeycomb, corning celcor, spiral and pin array (See Fig. 2.). Spiral stacks are made with several sheets of material wrapped around thin rods, the common spiral stack is made of mylar sheets wrapped around fishing wire. Parallel plates are assembled in layers where the preferred gap is in between 2 to 4 times the thermal penetration depth (δk) [8]. The honeycomb and corning celcor substrates are manufactured in abundance since catalytic converters in the exhaust of cars use these stacks. There are two methods to manufacturing the profile of the stack. The first method is laser cutting where a solid tube of ceramic is burnt by laser cutters, machining the substrates. The second method is dry pressing where a tool and die are used. Ceramic powder is poured into the die and compressed to the front profile specifications of the stack [9]. Sustainable advantages of the TAR are that the equipment requires small power densities to operate and can be powered by solar energy.

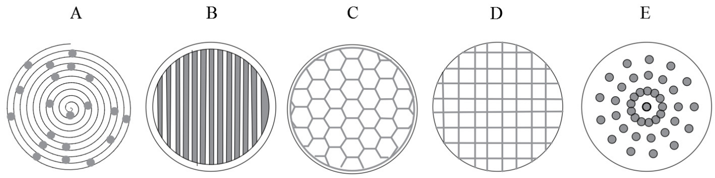


Fig. 2 Stack geometries: A. spiral stack, B. parallel plate, C. honeycomb, D. corning celcor, E. pin array

Guédra et al [10] found that ceramic substrates produce the greatest thermal exchange coefficients in terms of heat power for the stack and hot heat exchanger. Ceramic substrates, stainless steel, Nickel-chromium (NiCr) and reticulated vitreous carbon (RVC) foam were the stack materials compared. Ceramic substrates are generally selected as the stack material because of the low thermal conductivity and the low heat conduction occurring inside the stack. This material has a high heat capacity and can therefore withstand high temperatures. They are cost effective since they are mass produced for the automotive industry [11].

A considerable amount of research has been conducted on the stack performance and efficiency. Tijani et al [12] analysed the thermoacoustic performances of the acoustic refrigerator with reference to the stack position, normalised stack length, ratio of stack diameter to resonator diameter and its significant losses. The results reported give guidance on the identification of the highest performance based on the coefficient of performance (COP), acoustic power input and cooling load. Tartibu [13] investigated geometrical parameters (pore size, length and position) and noticed certain couples yielded maximum performance values. The paper proved that moving the stack closer to the pressure antinode enhanced the performance.

Geometrical parameters of the stack have been extensively researched. However, a common methodology has been adopted. The frequency is generally considered the independent variable, kept constant, and individual geometrical configurations are considered the dependent variable. The aim of this work is to investigate the geometrical aspects of the stack and study the performance of a thermoacoustic cooler system. Analysis will be conducted after data is captured from an experimental setup and test equipment. The paper consists of the use of frequency and coupled geometry parameters as non-independent variables and investigation of possible interdependent relationship. Results and conclusions increase the feasibility of this technology being introduced as an alternative refrigerator.

3. Experimental investigation of TAR

The main objectives of the experimental investigation are:

- To identify the specific resonant frequency for all selected geometrical configurations (stack length and positions) and;

- to measure the temperature difference at steady state for all selected geometrical configurations.

The thermoacoustic refrigerator test equipment consists of the following components, as shown in Fig. 3:

- Loudspeaker;
- quarter wavelength resonator of 780mm;
- ceramic stack.

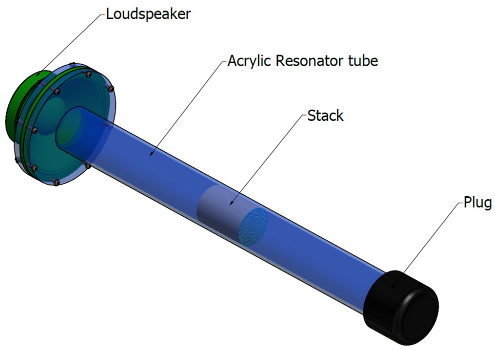


Fig. 3- TAR prototype

In this experiment, no heat exchangers are used as the aim is to study is to investigate the performance of the geometrical stack parameters, as well as focus on the material choice. A tone generator (NCH tone generator v3.12) was installed on a laptop. This program is used for producing tones and varying the sound frequency input to the speaker. The sinusoidal wave function was used in the experiment. An amplifier (Samson 130 Watt) was used to increase the magnitude of sound pressure. A multimeter was used to measure the input voltage and to obtain the input power. The input power to the loudspeaker was evaluated to be 12 W. The loudspeaker (Kenwood 210W) with a resistance of 4Ω was coupled to the resonator tube. The acrylic tube is 780mm long and has an inner diameter of 44mm. The stack position, porosity and stack length adopted in this experimental investigation are reported in Table 1. The resonator is filled with air. Two K-type thermocouples are connected on either side of the stack in order to measure the temperatures (T_{hot} and T_{cold}). The thermocouples have a threshold of 482 ºC and tolerance of +/- 2.2 ºC. The thermocouples are connected to a data acquisition system (NI DAQ 9211) which reads instantaneous temperature values versus time. The data acquisition system is connected to a laptop. Lab View 2014 was used for visualization. Refer to Fig. 3, for the integrated system set up.

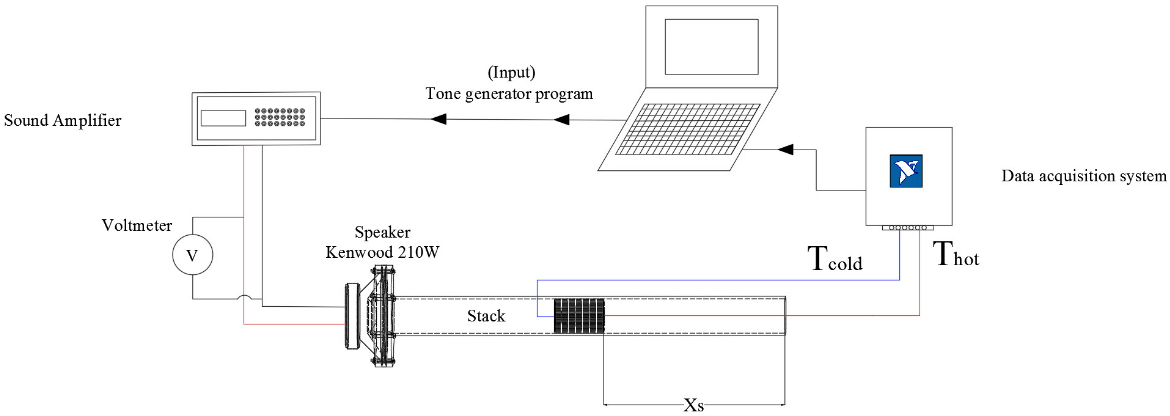


Fig. 4- System setup

Table 1- Stack properties and -geometrical samples of stack

	Size 1	Size 2

CPSI	230	300
Plate thickness [mm]	0.140	0.160
Plate spacing [mm]	1.467	1.675
Porosity [BR]	≈0.9	≈0.9
	Stack length[mm]	Stack positions from closed end [mm]
	100	500,400,300,200,100
	70	500,400,300,200,100
	48	500,400,300,200,100
	26	500,400,300,200,100

4. Results and discussion

In Fig. 5, the resonant frequency was determined for each stack position according to Fig. 4 and Table 1. A sample of results obtained for size 1 (230 CPSI) is reported. A scatter plot diagram with a polynomial trend line (for visual guidance) is used to show the relation between resonant frequency and stack position. The graph shows that resonant frequencies for each stack position are different. The temperature differences across each stack corresponding to the resonant frequencies were measured. Fig.6 shows the relation between the temperature difference across the stack and the stack position. A trend line (used for visual guidance) indicates that there is a maximum expected temperature difference when the stack is located closer to the pressure antinode (closed end).

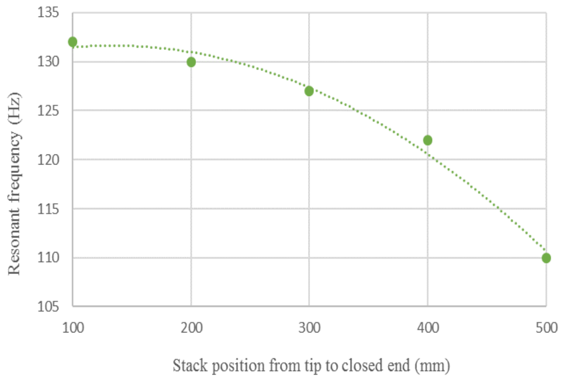


Fig. 5: Size 1 stack - resonant frequency vs stack position

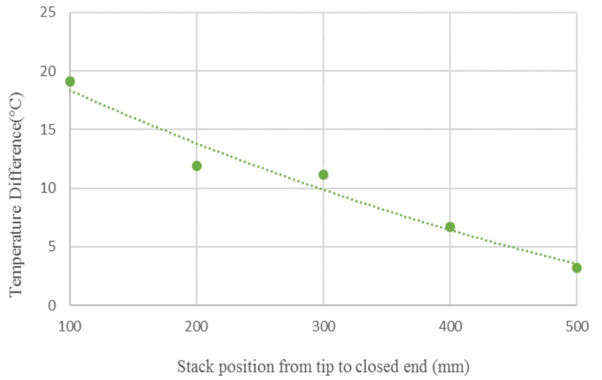


Fig.6: Size 1 stack – temperature difference vs stack position

Hen this TAR, a specific resonant frequency must be found in terms of porosity of the stack and position.

In Fig. 7 resonant frequencies as a function of stack lengths are shown. A sample of results obtained for size 1, located 100mm from the closed end are reported. There is a specific resonant frequency corresponding to each stack length. Interestingly, these results indicate there is an insignificant change (≈ 3 Hz) in resonant frequency as a function of the stack length. It must be noted that this TAR is a small scale prototype, therefore it has small variances in resonant frequencies which may not be the same result for an industrial TAR. In Fig 8, the temperature differences across each stack are plotted against the stack length for size 2, positioned 100mm from the closed end of the resonator tube. Intriguingly, the highest temperature difference was observed for the 70mm stack length, this clearly indicates that the relationship between the geometrical parameters and the measured temperature differences is nonlinear.

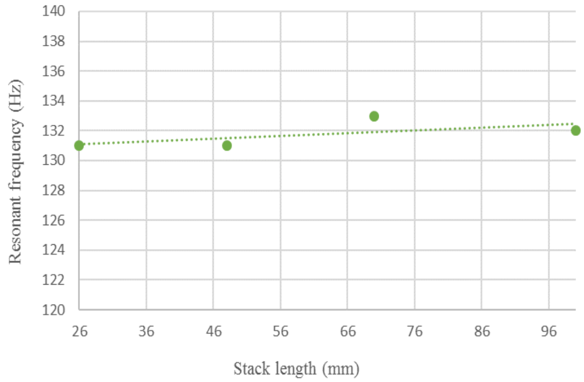


Fig.7: Size 1 stack - resonant frequency vs stack length

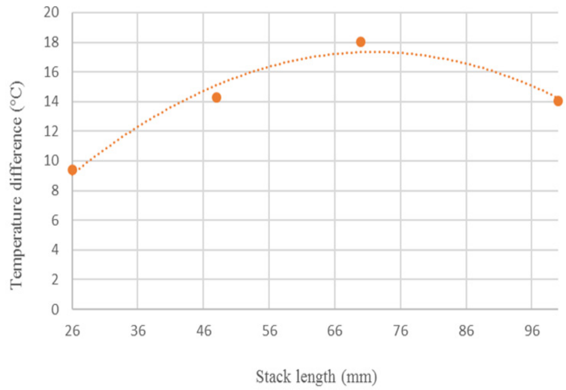


Fig.8: Size 2 stack – temperature difference vs stack length

5. Conclusion

In this paper an experimental set up was used to investigate the performance of the TAR consisting of a loudspeaker driven thermoacoustic refrigerator. Material choice and manufacturing of the stack are important factors affecting the performance or the efficiency of the TAR. One of the main attributes of the TAR, is the sustainability it offers. It is for these reasons that ceramic substrates were used as the stack choice for these experiments. Eight different samples were used in these experiments. Geometrical configurations such as porosity, stack length and stack position were used to study the performance of the TAR. The resonant frequencies corresponding to the highest temperature difference were identified for each geometrical configuration. The results obtained show that resonant frequency for each stack position were different. There is a maximum temperature difference when the stack is located closer to the pressure antinode. With regard to stack length the effect of the resonant frequencies was found to be insignificant. The relationship between the geometrical parameters describing the ceramic substrates, and the measured temperature difference related to the TAR performance were nonlinear. This suggests that further studies on the interdependence between the geometrical parameters and the corresponding frequencies are necessary.

5. Acknowledgements

This work was supported by the University of Johannesburg research fund.

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