Thermoacoustic refrigeration in different gases for different frequencies

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Thermoacoustic refrigerator is a device that transfers heat from a cold medium to warm medium by using sound energy as an input work. This investigation deals with the construction and performance of the thermoacoustic refrigerator. Three different gases of air, nitrogen and helium were used as working fluids in the resonance tube. The experiments were performed at different frequencies 300, 400, 500 and 600 Hz. The length of the tube was typically a half wavelength of the driving frequency. The position of the stack was studied experimentally and optimized for maximum temperature difference for different gases at different frequencies. It is observed that the helium gives the highest temperature difference as it has the highest sound speed. The experimental results were compared with previous published results and showed satisfactory agreement.

التبريد بالصوت هى ظاهرة تحول طاقة الصوت الى طاقة حرارية باستخدام طاقة الصوت كشغل داخل. تم فى هذا البحث تناول دراسة عملية لتصميم واداء ثلاجة صوت حرارية على هيئة ماسورة تحتوى على ثلاث غازات مختلفة وهم الهواء والنيتروجين والهليوم. تم استخدام ترددات مختلفة وهم ٣٠٠، ٤٠٠، ٥٠٠ و٦٠٠ هرتز مع تغير مسافة موضع المبادل الحرارى. طول الماسورة المستخدم يساوى نصف الطول الموجى للتردد المستخدم وذلك عن طريق المكبس داخل الماسورة. اظهرت النتائج ان اقصى فرق لدرجات الحرارة كان فى الهليوم نظرا لسرعة الصوت العالية خلاله. تم عمل مقارنة بين النتائج الحالية ونتائج منشورة حديثا عند تردد ٤٥٠ هرتز فى الهواء وكانت المقارنة مرضية.

Keywords: Thermoacoustic, Refrigeration, Frequency generator

1. Introduction

Thermoacoustic is a branch of science dealing with the conversion of heat energy into sound energy and vice versa. A device that converts heat energy into sound or acoustic work is called thermoacoustic heat engine or prime mover and the device that transfers heat from a low temperature reservoir to a high temperature reservoir by utilizing sound or acoustic work is called thermoacoustic refrigerator. Thermoacoustic effects, which convert heat energy into sound energy and vice versa based on that sound wave, are pressure waves. Thermoacoustic refrigerator uses sound energy, converted into work input, to transfer heat from low temperature medium to a high temperature medium. These sound waves propagate through the gas via molecular collisions. The molecular collision causes a disturbance in the gas which, in turn, creates constructive and destructive interference. The constructive interference makes the molecules compress, and the destructive interference makes the molecules expand. This principle is the basis behind the thermoacoustic refrigerator. One method to control these pressure disturbances is with standing waves. Standing waves are natural phenomena exhibited by any wave, such as light, sound, or water waves. Thermoacoustic devices are typically characterized as either standing wave or traveling wave configurations. Refrigeration riles on two major thermodynamic principles; first; fluid temperature rises when compressed and falls when expanded. Second, when two substances are placed in direct contact, heat will flow from the hotter substance to the cooler one. While conventional refrigerators use pumps to transfer heat on a macroscopic scale, thermoacoustic refrigerators rely on sound to generate waves of pressure that alternately compress and relax the gas particles within the tube. In a closed tube, columns of air demonstrate these patterns as sound waves reflect back on themselves after colliding with the end of the tube. When the incident and reflected waves overlap, they interfere constructively, producing a single waveform. This wave appears to cause the medium to vibrate in isolated sections as the traveling waves are masked by the interference. Therefore, these "standing waves" seem to vibrate in constant position and orientation around stationary nodes. These nodes are located where the two component sound waves interfere to create areas of zero net displacement. The areas of maximum displacement are located halfway between two nodes and are called antinodes. The maximum compression of the air also occurs at the antinodes. Due to these nodes and antinodes properties, standing waves are useful because only a small input of power is needed to create a large amplitude wave. This large amplitude wave then has enough energy to cause visible thermoacoustic effects. The thermoacoustic refrigeration consists of a loudspeaker, attached to one end of an acoustic resonator tube, which is closed at the other end and filled with the working fluid. They use air or other inert gases that do not have any harmful effect on the environment. The loudspeaker sustains an acoustic standing wave in the gas at fundamental resonance frequency. In the tube, a stack consisting of number of drinking pipettes and two heat exchangers are appropriately installed. The acoustic standing wave displaces the gas in the channels of the stack while compressing and expanding. Garret et al. [1] developed a new spacecraft Crycooler, which used resonant high-amplitude sound waves in inert gases to pump heat. This Crycooler was used in the space shuttle discovery. Tijuana et al. [2] studied the effect of some important thermoacoustic parameters such as the stack plate, by achieved temperature, as low as -65˚C, in their device. Jin et al. [3] used a thermoacoustic engine to drive a thermoacoustic refrigerator. Their experiments were focused on the characteristics of both the thermoacoustic refrigerator and the thermoacoustic engine. They obtained a temperature difference of approximately 120 K across the stack in this system. Efforts made to optimize the design of thermoacoustic coolers by improving the stack geometry, gas mixture, thermal insulation, duct and cone diameters, and other parameters.

An optimization scheme to achieve the best electro acoustic driver efficiency was developed by Wakeland [4] using equivalent electrical circuit theory. An equation was derived to calculate electro acoustic efficiency from known driver parameters. Optimization of the stack spacing for maximum COP or for maximum cooling power was experimentally investigated by Tijani et al. [5]. They observed that a stack spacing of about 3 times larger than the thermal penetration depth is optimal for Thermoacoustic refrigeration. Swift [6] documented the history of thermoacoustics Rott [7] developed theoretical and analytical foundation for thermoacoustic heat pumps and refrigerators. Recently, Emmanuel et al. [8] studied the oscillatory flow heat transfer at the heat exchanger of the thermoacoustic refrigeration system. The study identified significant factors that influence this heat transfer as well as the construction of the system. The results from the experimental study were correlated in terms of Nusselt, Prandtl and Reynolds numbers to obtain new correlation for the heat transfer at the heat exchanger. Belcher et al. [9] studied working gases suitable for use in thermoacoustic system. Wetzel and Herman [10] used a model based on the boundary layer approximation and the short stack assumption to calculate the work flux and heat flux ; they optimized the system by adjusting 19 design variables to achieve the best COP. Herman and Chen [11] studied a simplified model of heat transfer in heat exchanger and stack plates. They considered flat tubes as heat exchangers with the height of 0.2 mm equal to the stack plate thickness. These heat exchanger tubes were aligned with the stack plate causing no additional area blockage. Water was considered as the heat exchanger fluid. They studied the heat flux and temperature fields in the stack plate and the temperature distribution in the heat exchangers. They found that the temperature of the stack plate is two-dimensional and nonlinear near the edges, and one-dimensional and linear in the region away from the edges. They also concluded that cold-end and hot-end heat exchangers do not influence each other.

Mozurkewich [12] measured heat transfer from heated wires located at velocity antinodes in a standing acoustic wave. The Nusselt number was accurately predicted using a steady flow, forced-convection correlation based on an acoustic Reynolds number for high Reynolds numbers, in conjunction with a natural-convection model for low Reynolds numbers. More recently, Mozurkewich [12] performed experiments within a quarter-wavelength modular thermoacoustic refrigerator using aluminum heat exchangers with simple geometries. Worlikar et al. [13] performed numerical studies on a thermoacoustic refrigeration system with emphasis on thermally stratified flow in the neighborhood of an idealized thermoacoustic stack. Energy flux density around the heat exchangers was visualized and implications on the heat exchanger design were examined. Poese and Garrett [14] measured the performance of a thermoacoustic refrigerator driven at relatively high amplitudes. For the heat exchanger performance model, the study used a modified steady-state correlation obtained from estimated time-averaged convective heat transfer coefficient. Paek et al. [15] investigated the thermal performance of micro channel heat exchangers in a thermoacoustic cooling system. Calculation methods were developed for evaluating the oscillating flow heat transfer coefficients. Results from the study were correlated in terms of the Colburn-j factor and compared with results from steady flow measurements and predictions from boundary layer conduction model. The results showed that the boundary layer model did not accurately predict the heat transfer coefficients and the influence of Reynolds number on heat transfer performance. Masoud et al. [16] investigated the impact of the gas blockage for three cases; no heat exchanger, heat exchanger with small thermal contact area and heat exchanger with large thermal contact area. Experiments were conducted in a half-wavelength standing wave resonator. The position of the stack was optimized experimentally and was in good agreement with the theoretical value. The results showed that the gas blockage has a significant impact on the thermoacoustic process inside the stack. The temperature difference across the stack decreased with an increase in the gas blockage. The relationship between the gas blockage fraction and the temperature difference across the stack was linear. The impact of heat exchangers on the thermoacoustic process was also studied. The results showed that a heat exchanger with larger thermal contact area increases the heat exchange between the heat exchanger fluid and the stack, but reduces the cooling power and increases the work input to the stack due to the increased gas blockage. It was concluded that when thermoacoustic devices are used as a refrigerator, there is a compromise between the cooling power of the device and the heat exchanged with the heat exchangers. From the previous review, the study of thermoacoustic refrigeration for different gases and different frequencies was not studied. Therefore the present study aims to investigate gas type and acoustic frequency on the performance of thermoacoustic refrigerators.

2. Experimental set up

The general view of the experimental apparatus constructed is shown in fig. 1. The thermoacoustic refrigeration consists of resonance tube, gas, acoustic loudspeaker, stack amplifier, and frequency generator. The resonance tube is made from straight acrylic fiberglass of length 1.3 m with internal diameter of 5 cm and wall thickness of 6 mm. The length of the resonance tube was set equal to half the wave length of the acoustic waves. The most important component is the stack which facilitates heat transfer to and from the working fluid. The property of the stack plays an important part in the thermoacoustic device. The stack material has good heat capacity and low thermal conductivity. This low thermal conductively gives high temperature gradient across the stack. The stack consists of 128 drinking pipettes of inner diameter 4 mm while the stack is of 4.2 cm diameter and a length of 4 cm and is inserted inside the resonance tube. Two heat exchangers of spiral shape of the same surface area are used at each end of the stack. They are made of 5 mm inside diameter copper tubes and surface area of 15 cm^2 with two small water tanks. These tanks are 35 cm height and 15 cm in diameter and are connected to the two heat exchangers. A loud speaker 8 Ω resistance with maximum power of 300 watt was used as the acoustic driver. The loudspeaker has circular shape and is placed in fiber glass box and is installed at one end of the resonance tube. The loudspeaker was driven by a function generator at a frequency of 300 to 600 Hz. At the other end of the resonance tube, a movable piston allowing change length of the resonance tube according to the frequency of the acoustic driver. The piston rod is made of metallic material and has 4.8 cm diameter. The power amplifier is used to provide the required acoustic power to move the working fluid inside the tube at frequency range from 20 to 2000 Hz. Two thermocouples are fixed at each end of the stack to measure the temperature difference across the stack. The accuracy of the thermocouple was ± 0.1 °C. In order to change the position of stack, two copper tubes of 3 mm diameter are mounted to the tube which contains the stack extracting the piston. A pressure gauge was connected to the gas tank with accuracy of ± 0.1% of the full scale. Three different gases are used during the experiments; they are Air, Nitrogen and Helium. These gases are of different characteristics. The characteristics are listed in table 1.

Table 1
Used gases properties

Working fluid	K	a
Air	0.024	345
Nitrogen	0.024	247
Helium	0.15	945

The speed of sound in an ideal gas is given by the relationship:

$$a = \sqrt{\frac{\gamma RT}{M}}$$

where γ is, R is T

3. Results comparison and discussion

Experiments were carried out using air, nitrogen and helium .The frequency was changed from 300 to 600 Hz. The position of the stack inside the resonance tube Xs was changed during the experiments. The temperature difference across both sides of the stack ΔT was measured at each stack position and for different frequencies. The results of the temperature are plotted versus the stack position in figs. 2 to 4, for the different gases and frequencies. It is observed from fig. 2 that the maximum temperature difference does not depend on the frequency but on the stack position. The same phenomenon is observed for nitrogen and helium in figs. 3 and 4. The maximum temperature difference across both sides of the stack and the position of the stack at which the maximum temperature difference occurs are listed in table 3, for the different gases and frequencies.

The length of the resonator tube was set equal to half the wavelength of the acoustic wave for the required frequency. Increasing the frequency the length of the resonator tube decrease. A movable piston is attached to

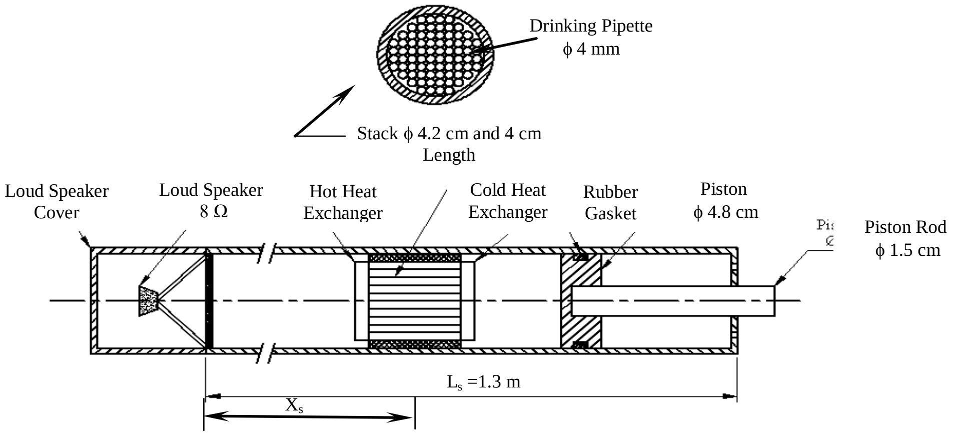

Fig. 1. Schematic of a thermoacoustic refrigerator.

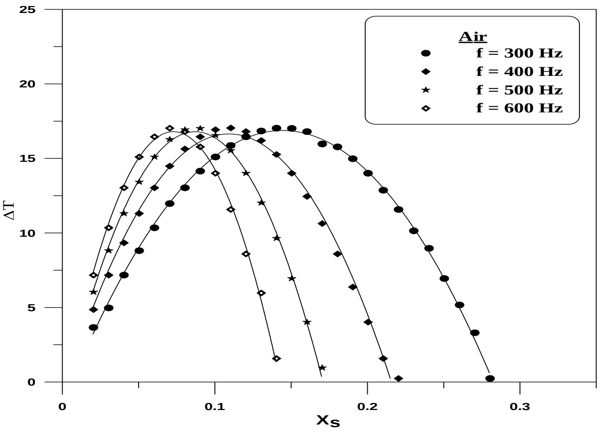

Fig. 2. Temperature difference across the stack (ΔT) versus the mid stack position (Xs) for Air for different frequency.

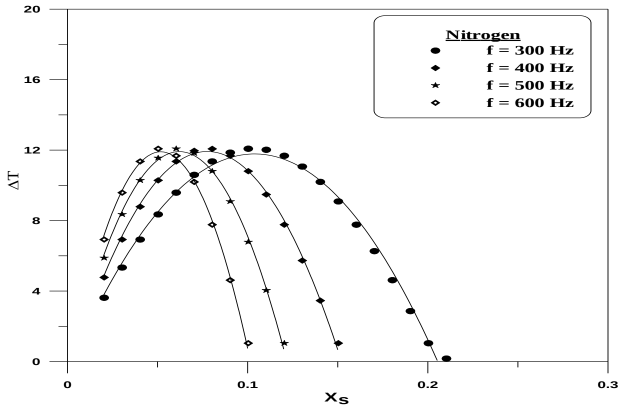

Fig. 3. Temperature difference across the stack (ΔT) versus the mid stack position (Xs) for Nitrogen for different frequency.

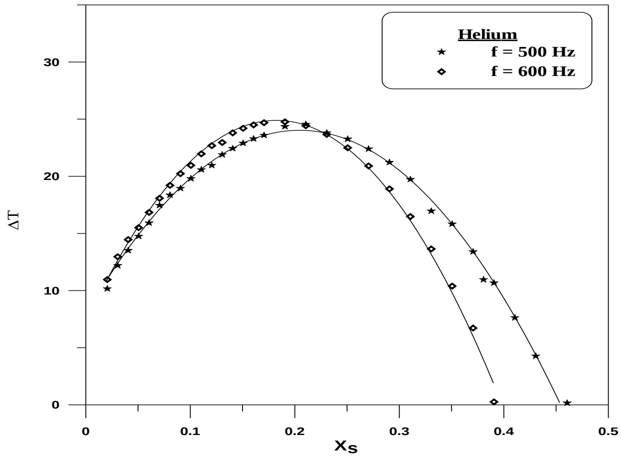

Fig. 4. Temperature difference across the stack (ΔT) versus the mid stack position (Xs) for Helium for different frequency.

the other end of the resonator tube which allows changing the length of the resonator tube, depending on the frequency of the acoustic driver. It is observed from table 3 that increasing the frequency does not affect the value of the maximum temperature difference across the stack but decreases the position of the stack at which the maximum temperature difference occurs. So it is recommended to use high frequency as the length of the resonator tube will decrease thus resulting in more compact device.

Fig. 5 shows a comparison between the three gases. The observations from both fig. 5 and table 3 point out that the helium gives the maximum temperature difference. This is due to its high sonic speed and high thermal conductivity but at longest stack position.

The data shown in figs. 2- 4 are correlated and listed in table 2, for the different three gases and at the different frequencies. These correlations are very useful because they are the direct and accurate method to get the local and maximum temperature difference in the tube for different three gases and different frequencies. Theses correlations are used analytically to get the position of stack at which the maximum temperature difference occurs.

Comparison between the present study and Masoud et al. [16] is showed in fig. 6. The differences between the two results are due to the fact that experimental results dependent on the all parameters in the test rig and outside environment especially the stack type which is the main component of the equipment causing the separation between hot and cold medium which facilitates heat transfer to and from the working fluid. Therefore, the characteristics of the stack have a significant impact on the performance of a thermoacoustic device. Our stack consists of drinking's pipette of inner diameter 4 mm. The stack is of 4.2 cm diameter and 4cm length and is inserted inside the resonance tube which is completely differed from Masoud et al. [16] stack which was made from a 0.13 mm thick Mylar sheet and length equal to 3 cm.

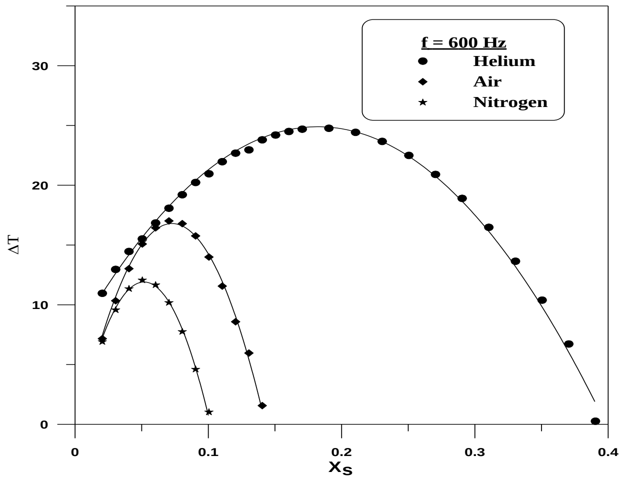

Fig. 5. Comparison between Air,Nitrogen and Helium temperature difference across the stack (ΔT) versus the mid stack position (Xs) at 600 Hz frequency.

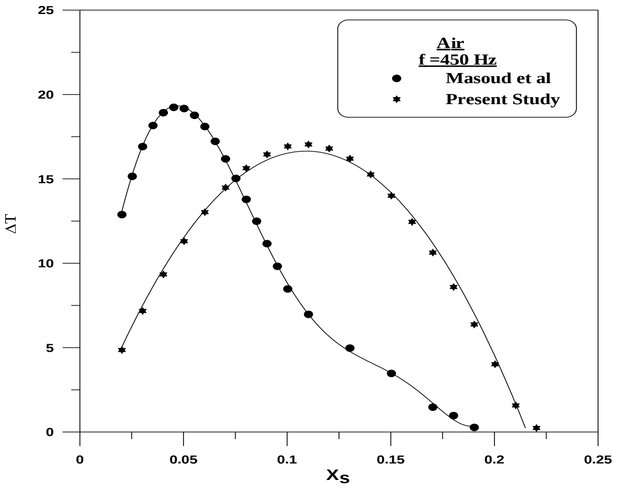

Fig. 6. Comparison with Masouad et al. [16] for air at 450 Hz frequency.

Table 2
Correlated equations for the experimental data

	Air
f = 300 Hz	$\Delta T = -1.5605 + 255.356 * X_s - 884.386 * X_s^2$
f = 400 Hz	$\Delta T = -0.849 + 320.359 * X_s - 1466.747 * X_s^2$
f = 500 Hz	$\Delta T = -1.317 + 415.977 * X_s - 2389.098 * X_s^2$
f = 600 Hz	$\Delta T = -1.308 + 497.549 * X_s - 3418.55 * X_s^2$
	Nitrogen
f = 300 Hz	$\Delta T = -0.537 + 237.19 * X_s - 1141.626 * X_s^2$
f = 400 Hz	$\Delta T = -0.987 + 332.82 * X_s - 2145.303 * X_s^2$
f = 500 Hz	$\Delta T = -0.979 + 415.3 * X_s - 3344.015 * X_s^2$
f = 600 Hz	$\Delta T = -0.924 + 495.904 * X_s - 4792.1 * X_s^2$
	Helium
f = 300 Hz	-
f = 400 Hz	-
f = 500 Hz	$\Delta T = 7.929 + 157.404 * X_s - 384.81 * X_s^2$
f = 600 Hz	$\Delta T = 7.214 + 194.09 * X_s - 532.629 * X_s^2$

Table 3
Maximum temperature difference for different frequencies and stack position

	Air	
	X_s	ΔT_{max}
f = 300 Hz	0.144	16.87
f = 400 Hz	0.109	16.64
f = 500 Hz	0.087	16.78
f = 600 Hz	0.072	16.79
	Nitrogen	
	X_s	ΔT_{max}
f = 300 Hz	0.103	11.78
f = 400 Hz	0.077	11.92
f = 500 Hz	0.062	11.91
f = 600 Hz	0.051	11.9
	Helium	
	X_s	ΔT_{max}
f = 500 Hz	0.204	24.02
f = 600 Hz	0.182	24.89

4. Conclusions

1. The thermoacoustic refrigeration is available but with small refrigeration capacity due to the low work input in the loud speaker.
2. The helium is more favorable gas for thermoacoustic refrigeration due to its high sonic speed and high thermal conductivity but it needs high expensive extracted cost and long tube to get maximum temperature difference.
3. The frequency has no effect on the cooling capacity and maximum temperature difference but affects the required tube length required to get this maximum temperature difference.

Nomenclature

A	Sound velocity (m/s),
f	Frequency (Hz),
k	Thermal conductivity (W/ m.K),
L_s	Stack length (m),
X_s	Stack position (m),
ΔT	Temperature difference across the two ends of stack (K),
R	The universal gas constant (8.314 J/mol K),
T	The absolute gas temperature (K),
M	The molecular weight of the gas in (kg/mol), and
γ	The adiabatic constant.

References

[1] S.L. Garrett, J.A. Adeff and T.J. Hofler, "Thermoacoustic Refrigerator for Space Applications", Journal of Thermophysics and Heat Transfer, Vol. 7 (4), pp. 595-599 (1993).

[2] M.E.H. Tijani, J.C.H. Zeegers and A.T.A.M. De Waele, "Construction and Performance of a Thermoacoustic Refrigerator", Cryogenics, Vol. 42 (1), pp. 59–65 (2002).

[3] T. Jin, G.B. Chen, B.R. Wang and S.Y. Zhang, "Application of Thermoacoustic Effect to Refrigeration", Review of Scientific Instruments, Vol. 74 (1), pp. 677–679 (2003).

[4] R.W. Wakeland, "Use of Electrodynamic Drivers in Thermoacoustic Refrigerators", Journal of the Acoustical Society of America, Vol. 107, pp. 827-832 (2000).

[5] M.E.H. Tijani, J.C.H. Zeegers and A.T.A.M. de Waele, "The Optimal Stack Spacing for Thermoacoustic Refrigeration", Journal of the Acoustical Society of America, Vol. 112, pp. 128-133 (2002).

[6] G.W. Swift, "Thermoacoustic Engines", J. Acoust. Soc. Am., Vol. 84 (4), pp. 1145–1180 (1988).

[7] N. Rott, "Thermoacoustic S", Adv. Appl., Vol. 20, pp. 135–175 (1980).

[8] Emmanuel C. Nsofor, Serdar Celik and Xudong Wang "Experimental Study on the Heat Transfer at the Heat Exchanger of the Thermoacoustic Refrigeration System", Applied Thermal Engineering, Vol. 27, pp. 2435-2442 (2007).

[9] J.R. Belcher, W.V. Slaton, R. Raspet, H.F. Bass and J. Lightfoot, "Working Gases in Thermoacoustic Engines", Journal of the Acoustical Society of America, Vol. 105 (5), pp. 2677–2684 (1999).

[10] M. Wetzel and C. Herman, "Design Optimization of Thermoacoustic Refrigerators", International Journal of Refrigeration, Vol. 20, pp. 3-21 (1997).

[11] C. Herman and Y. Chen, "A simplified Model of Heat Transfer in Heat Exchangers and Stack Plates of the Thermoacoustic Refrigerators", Heat Mass Transfer, Vol. 42, pp. 901–917 (2006).

[12] G. Mozurkewich, "Heat Transfer From a Cylinder in an Acoustic Standing Wave", J. Acoust. Soc. Am., Vol. 98, pp. 2209–2216 (1995).

[13] A.S. Worlikar and O.M. Knio, "Numerical Study of Oscillatory Flow and Heat Transfer in a Loaded Thermoacoustic Stack", Numerical Heat Transfer, Part A: Applications, Vol. 35 (1), pp. 49–65 (1999).

[14] M.E. Poese and S.L. Garrett, "Performance Measurements on a Thermoacoustic Refrigerator Driven at High Amplitudes", Journal of the Acoustical Society of America, Vol. 107 (5), pp. 2480–2486 (2000).

[15] I. Paek, J.E. Braun and L. Mongeau, "Characterizing Heat Transfer Coefficients for Heat Exchangers in Standing Wave Thermoacoustic Coolers", Journal of the

Acoustical Society of America, Vol. 118 (4), pp. 2271–2280 (2005).
[16] Masoud Akhavanbazaz, M.H. Kamran Siddiqui and Rama B. Bhat, "The impact of Gas Blockage on the Performance of a Thermoacoustic Refrigerator", Experimental Thermal and Fluid Science, Vol. 32, pp. 231–239 (2007).

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