COMPACT THERMOACOUSTIC COOLERS

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Abstract : The paper focuses on works carried out on compact coolers at LAUM, including recent developments. System architectures are described and the main experimental results are presented. Finally, performance of such small scale thermoacoustic devices are compared with the one obtained with standing wave device having similar stack. Slightly higher efficiency than in the standing wave system is found, yet at much smaller size.

1. Introduction

The compactness of thermoacoustic devices is a topic of continuing importance in fundamental thermoacoustics and in its practical applications. It is still a challenging topic to scale down the devices without compromising their performance. Several attempts to reduce the size of thermoacoustic refrigerators have been carried out since the early 2000's. Initially, some authors proposed to reduce the dimensions of the systems, while maintaining a classical design by raising the acoustic frequency. Thus, miniaturized standing-wave refrigerators were developed using both a piezoelectric actuator as sound source and a micro machined stack whose dimensions are matched with the high working frequency [1-3]. However, the performance of these systems is limited in terms of both heat extracted from the cold source and coefficient of performance (COP).

Thus, other more efficient architectures have been developed. Research on such architectures has been conducted in recent years at Laboratoire d'Acoustique de l'Universite du Maine (LAUM). The compact coolers developed in this framework involve non resonant small cavity fitting the stack dimensions, instead of a half- (or quarter-) wavelength acoustic resonator. The small cavity is driven by a set of loudspeakers coupled through the stack. Tuning all speakers allows controlling both the acoustic pressure field and the particle velocity field inside the stack. The acoustic pressure and the particle velocity are not linked anymore by standing wave or travelling wave conditions, and can then be managed independently. Moreover, the working frequency is not related to resonance conditions, therefore either a quasi-isothermal stack (regenerator) or a quasi-adiabatic stack can be used in the same cavity. Then, optimal acoustic field for thermoacoustic process can be reached in terms of frequency, pressure amplitude, velocity amplitude and phase difference between pressure and velocity.

The aim of this paper is to focus on work carried out on this subject at LAUM, including recent developments. System architectures are firstly described. Analytical model of their behavior are then briefly given and some experimental results are presented. Finally, performance of such small scale thermoacoustic devices are compared with the one obtained with standing wave device having similar stack.

2. Compact cooler description

A first kind of compact thermoacoustic device has been designed at LAUM in accordance with patent requirements [4]. A schematic view of this device is given in Figure 1. It is a non resonant thermoacoustic device in which the resonator is replaced by a cavity fitting the dimensions of the stack. The acoustic pressure and the particle velocity are generated in the stack by a set of loudspeakers: a couple of face-to-face loudspeakers (supplied with electrical voltages in phase) generates the pressure field in the cavity, while another couple (supplied with electrical voltages $\pi/2$ out of phase) generates the particle velocity field along the z axis. The acoustic pressure and the particle velocity are not linked anymore by standing wave or travelling wave conditions, and can then be managed independently. Particularly, their amplitude ratio and relative phase can take any value. The working frequency is not imposed by resonance conditions anymore, so a diminution of the dimensions of such a system does not come necessarily with an augmentation of this working frequency. Consequently, acoustic pressure, particle velocity and frequency can be easily and independently controlled in order to create an optimal acoustic field and to monitor it during the thermoacoustic process.

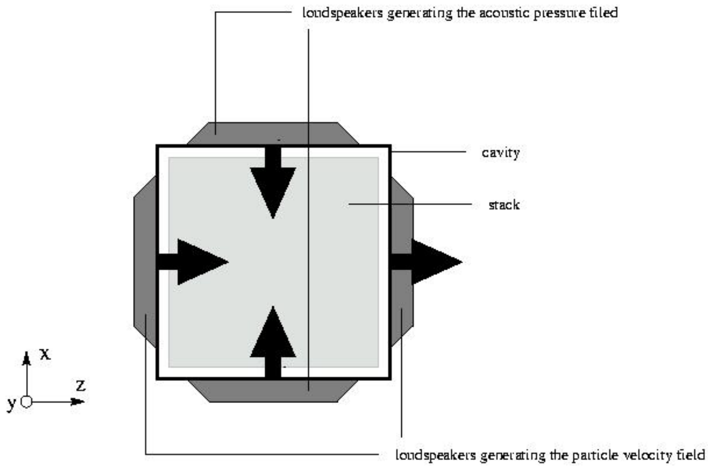

Figure 1: Compact thermoacoustic cooler using four acoustic sources.

Experiments on this prototype have showed that the particle velocity along the x axis close to the loudspeakers generating the pressure has the same order of magnitude as the optimal particle velocity generated along the z axis. Thus, the parcels motion between two plates of the stack is not a rectilinear motion anymore, but an ellipsoidal one. Then, the associated thermoacoustic heat transfer becomes a two-dimensional one and, consequently, the temperature difference is not necessarily established along the z-axis, as in a classical resonant thermoacoustic refrigerator. Moreover, this additional particle velocity along the x-axis leads to a significant additional global heating of the stack due to viscous dissipation.

These effects have then been taken into account in the design of a second generation of compact refrigerator prototype. A sketch of this second device is presented in Fig. 2. Similarly to the previous prototype, the thermoacoustic core almost fills the cavity, but it is surrounded by a peripheral channel. Only two loudspeakers are used in this prototype. The ends of the stack can then be considered set on either side of an acoustic inner source (labeled 1) which then creates the monochromatic displacement field needed in the acoustic process, in a frequency range such than the wavelength remains much greater than the dimensions of the cavity. A quasi-uniform pressure field is driven at the same frequency by another source (called outer source, labeled 2) set on a wall of the cavity. Similarly to the previous prototype, the working frequency, the amplitude and the phase difference between the pressure and the velocity fields can be tuned for optimizing the performance of the device. With this co-axial design, the particle velocity is uni-directional, as well as the main temperature gradient generated along the stack. This facilitates the implantation of heat exchangers.

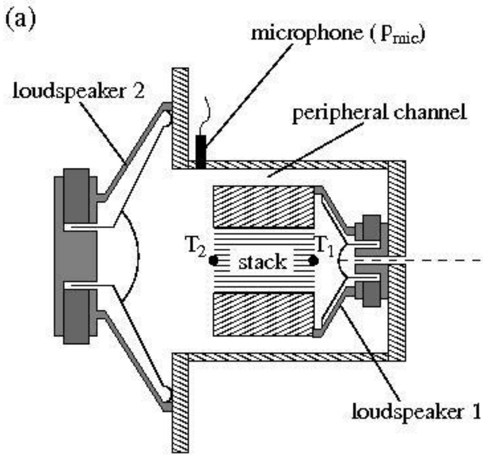

Figure 2: Co-axial compact thermoacoustic cooler.

3. Optimal acoustic field

An electrical network equivalent to the compact cooler is given on Figure 3, showing that the pressure and the velocity in the stack are easily controlled from the electrical tensions provided to both loudspeakers [6]. In 2006, Poignand et al. [4] have shown analytically that the thermoacoustic process in a stack can be optimized when tuning the acoustic field to optimal values of the acoustic pressure amplitude, the particle velocity amplitude, and their relative phase. The optimal values of particle velocity amplitude and relative phase depend on the frequency, on the shape and the dimensions of the stack, and on the thermo-physical properties of the fluid and the stack, while the optimal value of the acoustic pressure is the maximum pressure level which can be generated within the stack. This optimal field can easily be tuned within the stack of the non resonant compact coolers considered herein.

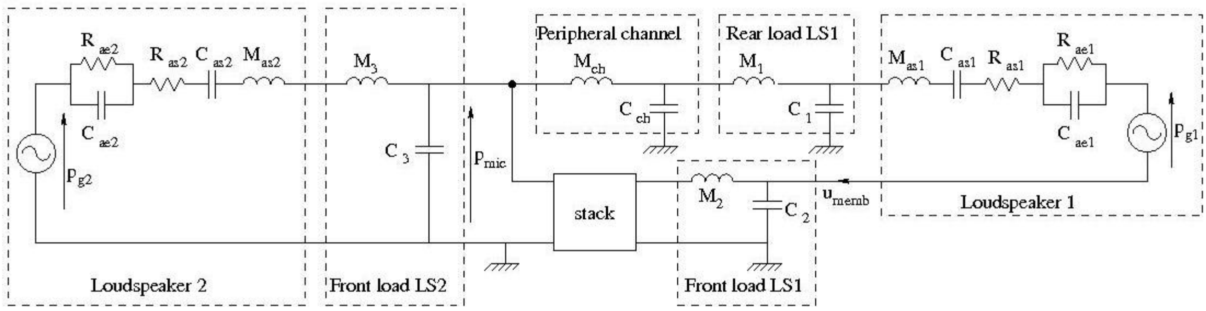

Figure 3: Electrical network equivalent to the co-axial compact cooler.

Experiments have been conducted on a prototype [7]. Experimental temperature difference between the stack ends are given in Figure 4. It shows the influence of the three acoustic parameters (the acoustic pressure amplitude p, the particle velocity amplitude u and the relative phase $\varphi = \varphi_u - \varphi_p$) on the compact system performance. The effect of each of the three acoustic parameters is investigated independently by fixing the two others parameters at their theoretical optimal value. Note that in this setup, the pressure peak amplitude is set to p = 1000 Pa which is close to the maximum pressure that can be generated by the loudspeaker 2 without harmonic distortion.

Figure 4.a shows the evolution of the temperature difference ΔT normalized by its maximum value ΔT_{max} as a function of the acoustic pressure p when $u = u_{opt}$ and $\varphi = \varphi_{opt}$. As predicted by the linear steady state theory [5] (solid line), the experimental results obtained

(crosses) show that the temperature difference ΔT increases with acoustic pressure. Figure 4.b shows the evolution of the temperature difference ΔT normalized by its maximum value ΔT_{max} as a function of the velocity amplitude u (when $p = p_{max}$ and $\varphi = \varphi_{opt}$). A good agreement is obtained between the theoretical predictions (solid line) and the experimental results (crosses). Especially, the experimental optimal velocity amplitude is found close to the theoretical one (u_{opt} = 1.4 m.s^{-1} for the experimental device under test). The normalized temperature difference $\Delta T/\Delta T_{max}$ versus the relative phase φ (when $p = p_{max}$ and $u = u_{opt}$) is shown in Fig. 4.c. When the phase shift φ varies between (-3π/4) and (π/4), the temperature difference $\Delta T/\Delta T_{max}$ is positive and the cold-side of the stack is near the loudspeaker 1 controlling the velocity, whereas for a phase φ comprised between π/4 and 5π/4, the temperature difference is negative and the cold-side stack end is located near the loudspeaker 2 controlling the pressure. Thus, it is worth noting that the cold-side stack end location can be fixed by the phase φ. From the experimental results presented in Fig. 4.c, it can be noticed that there is an optimal phase $\varphi_{opt,exp}$ = 3π /4 rad which corresponds to the theoretical optimal phase. However, the evolution of the experimental normalized temperature difference does not fit completely the theoretical one. This difference is due to the heating of the loudspeaker voice-coil controlling the velocity. This heating is added to the thermoacoustic heat flux and leads to an increase of the stack end temperature near the loudspeaker 1.

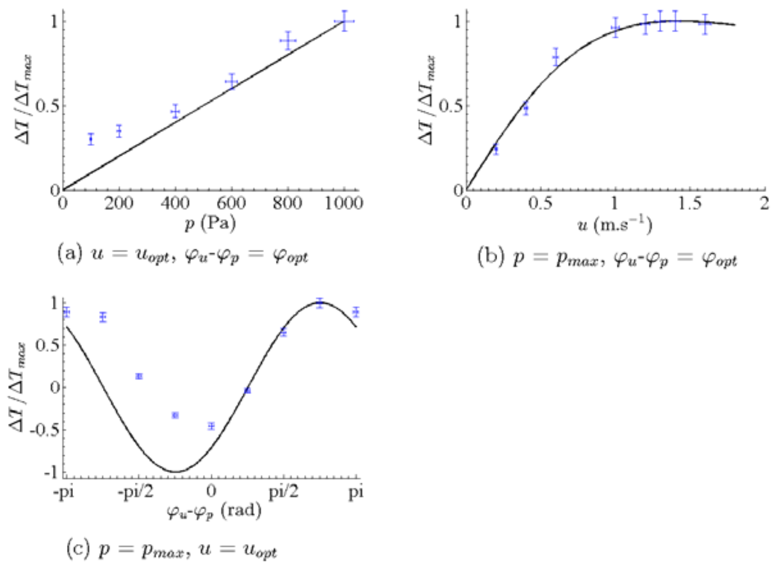

Figure 4: Normalized temperature difference $\Delta T/\Delta T_{max}$ between the stack ends measured (×) and calculated (straight line) as a function of (a) the acoustic pressure p, (b) the particle velocity amplitude u and (c) their relative phase φ .

4. Comparison with resonant thermoacoustic coolers

Using the electrical network given in Figure 3 and the classical thermoacoustic theory allows the prediction of the theoretical temperature difference and COP obtained in a co-axial compact cooler tuned at its optimal operating point. This theoretical performance can then been compared with the one of a conventional standing wave acoustic refrigerator when using similar stack in both devices.

The standing wave cooler considered for the comparison consists of a half wavelength straight resonator driven by an acoustic source. The source is chosen to be the same loudspeaker as the one which controls the acoustic pressure field in the small cavity cooler.

The resonator length is adjusted in such a way that the resonance frequency of the system is the working frequency of the compact device (i.e. f = 200 Hz for the device under test). The same stack is used for both the compact device and the standing wave cooler. In the standing wave cooler, the stack is set at its better location along the resonator for which the temperature difference is maximal [4]. The small cavity cooler is set at its optimal working point. To fulfill the comparison of the two devices, their achieved temperature difference ΔT, thermoacoustic heat flux Q and global efficiency η, are compared when the same electric power is provided to the sources (here, P_{el} = 7.7 W). Actually, in the case of the compact device, P_{el} represents the total electric power provided to the two loudspeakers. The theoretical acoustic field in the stack as well as theoretical performance is given in Tab. 1 for both systems.

Small cavity cooler	Standing wave cooler
Acoustic field in the stack	
p = 1000 pa	p = 1335 pa
u_{opt} = 1.43 m.s^{-1}	u_s = 1.27 m.s^{-1}
φ_{opt} = 3π/4 rad	φ_s = π/2 rad
Theoretical performance	
ΔT_{max} = 15.8 K	ΔT_s = 13.8 K
Q_{max} = 0.17 W	Q_s = 0.15 W
P_{el} = 7.7 W	$P_{el,s}$ = 7.7 W
η = 2.14%	η_s = 1.88%

Table 1: Theoretical comparison between the behaviour of a small cavity cooler and the behaviour of a standing wave cooler.

3. Conclusion

The experimental results presented here illustrate the thermal behaviour of compact thermoacoustic devices as a function of the acoustic field inside the stack. They validate theoretical results, namely the existence of an optimal acoustic field leading to better performance in terms of temperature difference, heat flux or COP. Then, a theoretical comparison with performance reached with classical device having equivalent stack (standing wave device) show the potentiality of this compact thermoacoustic cooler. In particular, beyond its compactness and flexibility, the global efficiency of the proposed device is greater than, or at least of the same order of magnitude as, that of classical devices having equivalent stack although it is much smaller.

5. References

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