SIMULATION OF FLOW AND HEAT TRANSFER IN THERMOACOUSTIC REFRIGERATOR USING A 3-D PERIODIC CELL STRUCTURE

A.I. Abd El-Rahman*, W.A. Abdelfattah, and M.A. Fouad

The Department of The Mechanical Power Engineering, Faculty of Engineering, Cairo University, Giza 12613, Egypt.
**Corresponding author's e-mail: aiarahman@eng.cu.edu.eg*

Keywords: *Thermoacoustic Refrigerator/Cooler, Oscillating-Flow behavior, Flow Streaming, 3-D Simulation, CFD Analysis*

Introduction

The thermoviscous behavior of the oscillating gas within the porous medium of a thermoacoustic refrigerator enables the conversion of sound into heat in the process of typical standing thermoacoustic refrigeration systems. Several nonlinear mechanisms, such as harmonics generation, self-induced streaming and possible turbulence, cause complicated flow behavior and influence the performance of such devices. Few analytical and 2-D numerical approximations [2, 5] describe the flow field and the energy flux density in standing devices comprising stacks of parallel plates, but almost no 3-D simulation has been developed that directly models the large-amplitude excitations and enables the prediction of the oscillating-flow behavior within a porous medium made of square channels. This work builds on existing effort [1], and has the objective of extending the 2-D analysis of thermoacoustic couples into a 3-D CFD simulation of a thermoacoustic refrigerator. The stack is made of cordierite and consists of a large number of small square channels (600 CPSI). Each channel is 60-mm-in-length and has a transveral width h of 0.92 mm and a wall thickness t of 0.12 mm. This work also investigates the existence of non-linear phenomenons, such as DC-streaming.

Numerical Model Setup

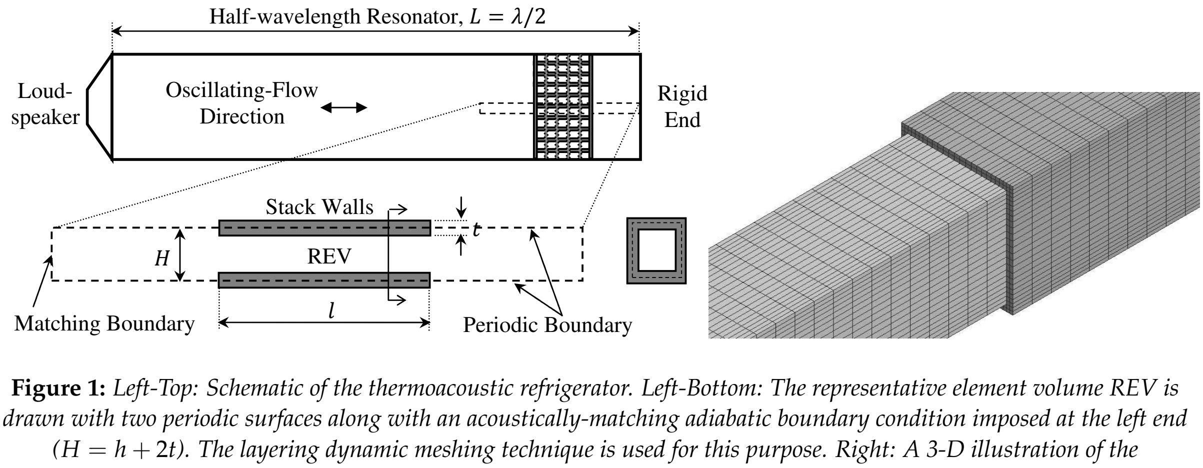

Figure 1: *Left-Top: Schematic of the thermoacoustic refrigerator. Left-Bottom: The representative element volume REV is drawn with two periodic surfaces along with an acoustically-matching adiabatic boundary condition imposed at the left end ($H = h + 2t$). The layering dynamic meshing technique is used for this purpose. Right: A 3-D illustration of the computational mesh of the periodic cell structure. The solid and gas domains are represented by large numbers of hexahedral elements. Here, the solid mesh is suppressed for clarity.*

The cooler geometry and domain meshing are shown in Fig. 1. For the sake of simulation and model validation, the current geometry and operating conditions follow the experimental setup of Lotton et al. [3]. The system is excited with an acoustic frequency of 200 Hz and acoustic pressure amplitude of 1500 Pa. The resonator has a square cross section and filled with air at atmospheric pressure and ambient temperature. The numerical model is constructed such that the stack centre is positioned at a distance 140 mm from the resonator closed end. The domain is carefully discretized to properly capture the thermoviscous interactions of the oscillating-flow with the stack walls. In the transversal direction, the mesh is distinguished into three concentric regimes, depth of each corresponds to the viscous diffusion thickness $\delta_\nu = \sqrt{2\nu/\omega}$. Here, ν and ω are the gas kinematic viscosity and angular frequency, respectively. For instance, a typical run involves a million of computational cells. The second-order upwind finite-volume implicit-time algorithm is used along with the conjugate heat transfer algorithm (ANSYS FLUENT).

Prelimnary Results

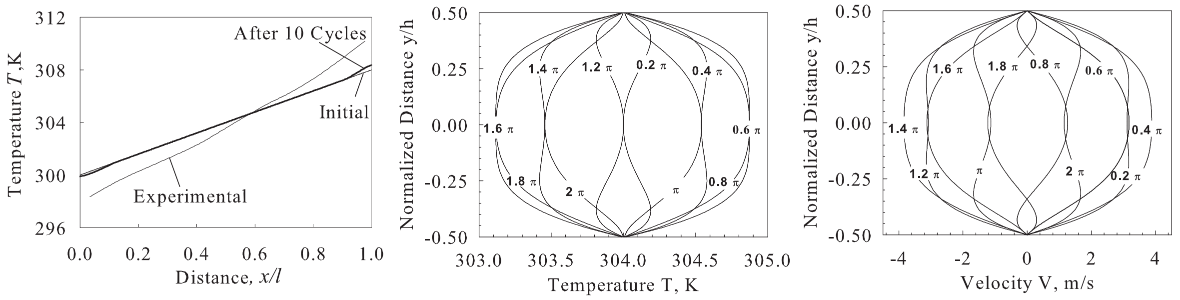

Figure 2: *The initially-imposed temperature distribution and its further development (Left). Laminar fully-developed temperature (Middle) and axial-velocity profiles (Right) at 10 different instants. The flow behavior is generally in agreement with that theoretically reported by Panton [4].*

Figure 2 shows the instantaneous temperature and velocity profiles for 36°-increments over one period. The stationary system response is predicted and the numerical values are presented in comparison with reported test data. Figure 3 illustrates the non-zero mean (cycle-average) velocity field, calculated over the last acoustic cycle.

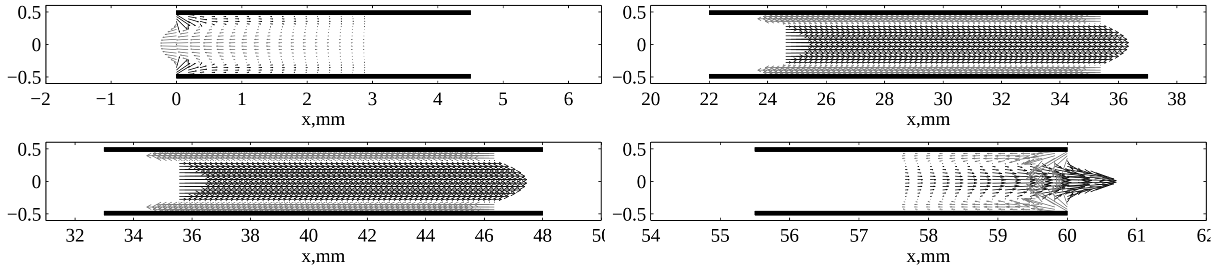

Figure 3: *Vector plot of the non-zero mean velocity field within the stack and at the stack extremities, demonstrating the existence of the DC-streaming.*

References

[1] Abd El-Rahman, A. I. and Abdel-Rahman, E. "Computational Fluid Dynamics Simulation of a Thermoacoustic Refrigerator". Journal of Thermophysics and Heat Transfer, **28**, (2014), 78 – 86.

[2] Cao, N., Olson, J. R., Swift, G. W., and Chen, S. "Energy flux density in a thermoacoustic couple". The Journal of the Acoustical Society of America, **99**, (1996), 3456–3464.

[3] Lotton, P., Blanc-Benon, P., Bruneau, M., Gusev, V., Duffourd, S., Mironov, M., and Poignand, G. "Transient temperature profile inside thermoacoustic refrigerators". International Journal of Heat and Mass Transfer, **52**, (2009), 4986 – 4996.

[4] Panton, R. L. *4^{th} Ed., Incompressible Flow.* John Wiley & Sons, Inc. (**2013**).

[5] Worlikar, A. S. and Knio, O. M. "Numerical Simulation of a Thermoacoustic Refrigerator: I. Unsteady Adiabatic Flow around the Stack". Journal of Computational Physics, **127**, (1996), 424 – 451.