PROPAGATION OF PRESSURE PULSES IN RECTANGULAR ENCLOSURES USING THE LATTICE BOLTZMANN METHOD

Conference Paper · August 2022

Johan Augusto Bocanegra
University of Genoa

Davide Borelli
University of Genoa

PROPAGATION OF PRESSURE PULSES IN RECTANGULAR ENCLOSURES USING THE LATTICE BOLTZMANN METHOD

Johan Augusto Bocanegra and Davide Borelli

Università degli Studi di Genova, Genova, Italy
email: augusto.bocanegra@edu.unige.it

Pulses are often used to determine acoustical characteristics of enclosures (such as room reverberation time). The extinction of the acoustical pulse depends mainly on viscous attenuation in the propagation medium and absorption by the materials of the enclosure (walls, ceilings, and floor). The geometry of the enclosure is directly linked with these two physical mechanisms: the former mechanism is linked with the volume of the room, while the latter with its surfaces. The Lattice Boltzmann Method is gaining attention in acoustics because it is a numerical method that intrinsically simulates the wave propagation, and has remarkable parallelization possibilities. A simple two-dimensional model was implemented to simulate the propagation of a pressure pulse in rectangular-shaped enclosures (cavities). Different geometric ratios were tested for a fixed enclosure area. The single relaxation time BGK collision operator was used in a *D2Q9* lattice. The pulse extinction time was determined as an analogy to the reverberation time. In the numerical model, the relaxation time controls the media attenuation, and the lower this value is (always >0.5 to ensure stability), the less attenuation occurs. The geometric ratio affects the extinction time following the expected relationship; extinction time is proportional to the area to perimeter ratio. This work shows that the LBM can be applied to study acoustic propagation in enclosures. Future works must consider three-dimensional domains, stochastic noise, harmonic waves, and a more stable collision operator that reduces the media attenuation without inducing instabilities.

Keywords: LBM, reverberation, Gaussian pulse, rectangular room, numerical methods

1. Introduction

The acoustic qualities of rooms and other enclosed places are routinely assessed using acoustic pulses.The physical principles that govern the extinction of an auditory pulse are intimately tied to the geometry of an enclosure: the viscous attenuation is influenced by the size of the space, while absorption by walls, ceilings, and floors is determined by its surface. A two-dimensional approach must consider the surface area and perimeter of the walls instead of the volume and surface area.

The Lattice Boltzmann Method (LBM) is gaining attention in diverse areas [1–3] thanks to its unique approach and strong parallelization capabilities. The current status of the LBM and its possible applications in heat transfer and aeroacoustics can be found in [4]; the variants of the LBM such as cumulant, entropic, or multiple relaxation time (MRT) models improve the stability of the most common single relaxation time LBM model. This numerical method has found several applications in aeroacoustics, musical acoustics, and porous absorption. Gaussian pulse propagation in LBM has been previously studied by several authors: developing a comparison between Bhatnagar-Gross-Krook (BGK) and MRT collision models [5], studying dissipation and dispersion properties of a planar gaussian pulse [6], or extensions of the method to consider diatomic gases and adjustable sound speed [7–9]. In this work, the simplest BGK-LBM is evaluated as a preliminary approach to use this method in room acoustics. The propagation and the decay of the acoustic pulse after multiple reflections in an enclosure with rigid walls is considered, examining the effect of the shape and the diffusivity of the medium.

2. Methods

This study was performed using a two-dimensional model. A sketch of the simulated geometry is presented in Fig. 1. Different rectangular enclosures characterized by a shape factor Lx/Ly were considered. A pressure pulse propagates from the corner of the enclosure where the source was located following the recommendations for a *survey* measurement ISO 3382-2:2008 [10]. The pressure variations calculated in different points (receivers) were used to determine the decay of the pulse. The walls were considered hard (bounce-back) boundaries. Preliminary proves where performed with porous walls.

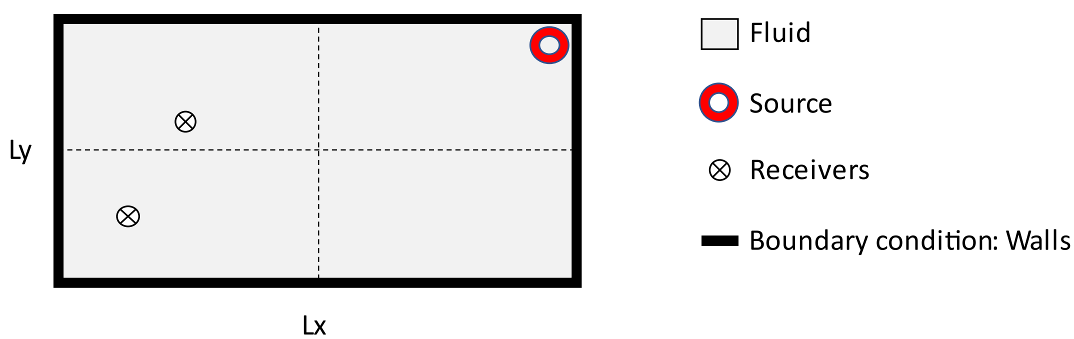


Figure 1: Sketch of the considered geometries.

2.1 Lattice Boltzmann Method

The numerical simulations were performed using the LBSim [11] open-source software implementation oof the LBM. This numerical method solves the discretized Boltzmann equation (Eq. (1)) for the transport of the probability density function or *populations* f_i:

$$f_i(\boldsymbol{r} + \boldsymbol{c_i}\Delta t, t + \Delta t) - f_i(\boldsymbol{r}, t) = -\frac{1}{\tau}\left(f_i(\boldsymbol{r}, t) - f_i^{eq}(\boldsymbol{r}, t)\right) \quad (1)$$

Figure 2 shows the nine populations f_i at each node of a two-dimensional grid (lattice) *D2Q9* [1]. In this lattice, eight populations are propagated to the neighbor node, and one population rests in the same node. Note that the populations are represented by arrows that contain the discretized velocity base; those arrows indicate the stream direction of the populations.

The solution algorithm is implemented in two steps:

- **stream step:** the probability density function propagates from one node to the neighbor nodes in each lattice;
- **collision step:** the discretized density functions that arrive at every single node collide between them, and a new set of populations are ready to stream and repeat this algorithm.

To calculate the collision between the populations, the collision operator BGK [12] is used (right side of Eq. (1)). This collision operator represents a relaxation of the incoming populations $f_i(\boldsymbol{r}, t)$ to the equilibrium populations f_i^{eq} with a characteristic relaxation time τ. Bounceback boundary conditions were used for the walls.

It is known that this computational parameter is linked to the kinematic viscosity of the fluid, Eq. (2):

$$\nu = (\frac{\Delta x}{\Delta t})^2(\tau - \Delta t/2) \tag{2}$$

and therefore to the timestep. During the simulations, the relaxation time was changed (1, 0.7, 0.6, 0.51) to observe its effect on the pulse attenuation. It can be noted that $\tau > 1/2$ is needed to ensure a non-negative viscosity. The resolution (L/Δx) of the lattice was also changed. After fixing the spatial resolution, the calculation of the time resolution and Δt is necessary to find the equivalence between computational units and physical units. Different ways can be implemented to determine Δt, for example using the value of the sound speed $c_s = \Delta t/\Delta$x, or the Eq. (2). In this work the results are presented in LBM (computational) units.

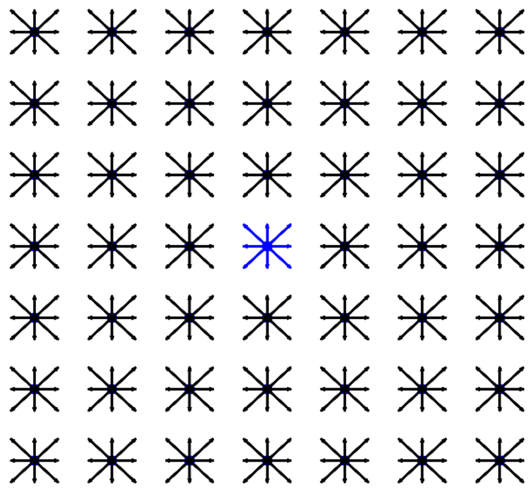


Figure 2: D2Q9 lattice.

3. Results and discussion

The simulations ran between 1 and 2 mega-site updates per second (MSUPS). MSUPS are commonly used to evaluate the computational performance. The total computational time depends on the lattice size and approximately went from 10 minutes (100x100) to almost 2 hours (800x800). To increase the computational performance it is possible to use a multicore platform subdividing the lattice into small segments to allow parallel calculations. It is also recommended to avoid input/output operations, that commonly imply a bottleneck, since it is necessary the communication and synchronization of all the cores.

3.1 Relaxation parameter

Figure 3 shows the post-processing of the pressure signals to determine the decay rate (dB/time steps) and the computational decay time (timesteps necessary to decrease the pressure amplitude by 60 dB). The pressure signal is converted to decibels with reference to the maximum value of each signal, corresponding to 0 dB. An envelope was adjusted to the local maximums of each signal. The decrease in the signal with time can also be noted, an early decay for the first reflexions and a later decay with a linear trend.

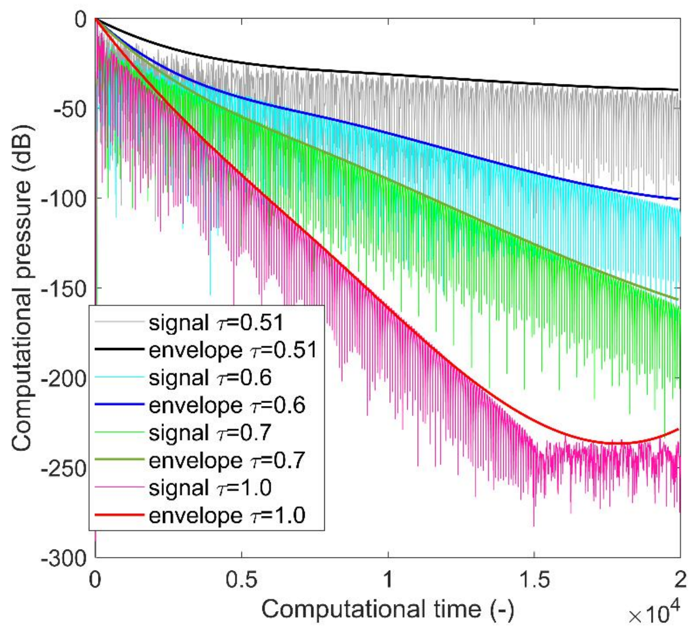


Figure 3: Pressure signal and envelope used to determine the decay rate and the extinction time. Square enclosure (100x100 cells).

Figure 4 presents some propagation characteristics (source located at the center), such as the initial shape of the pulse and the first reflections on the walls. The isotropy of the model is qualitatively perceptible in this figure. The wavefront adopts a circular shape even with the coarse lattice considered. When the relaxation parameter is reduced near the lower limit (0.5), the decay rate decreases, but effects related to nonlinear instabilities can be noted (Fig. 5).

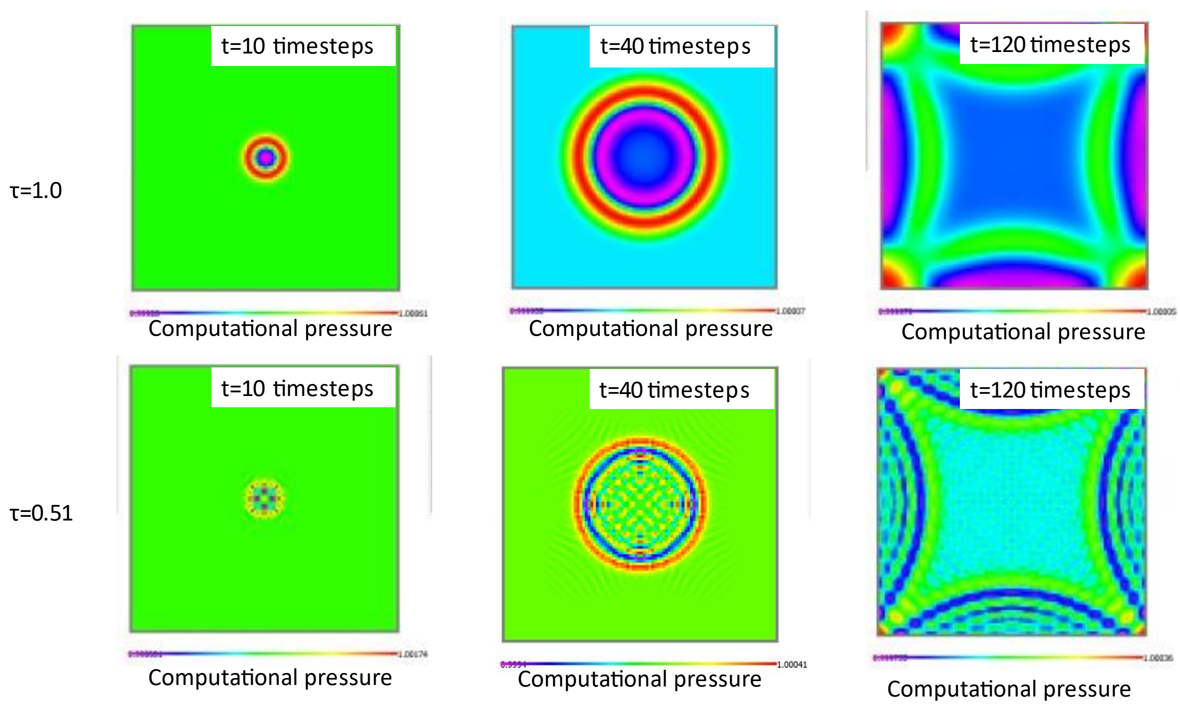
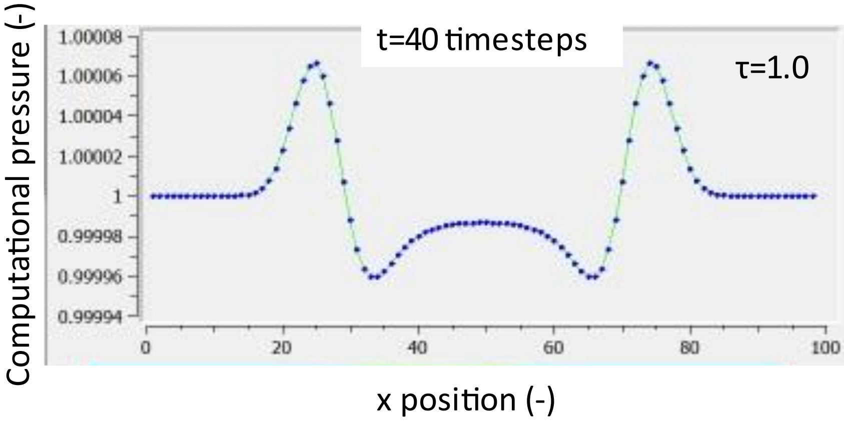


Figure 4: Square enclosure (100x100 cells). (a) Extinction time vs. tau (b) decay rate vs. time.



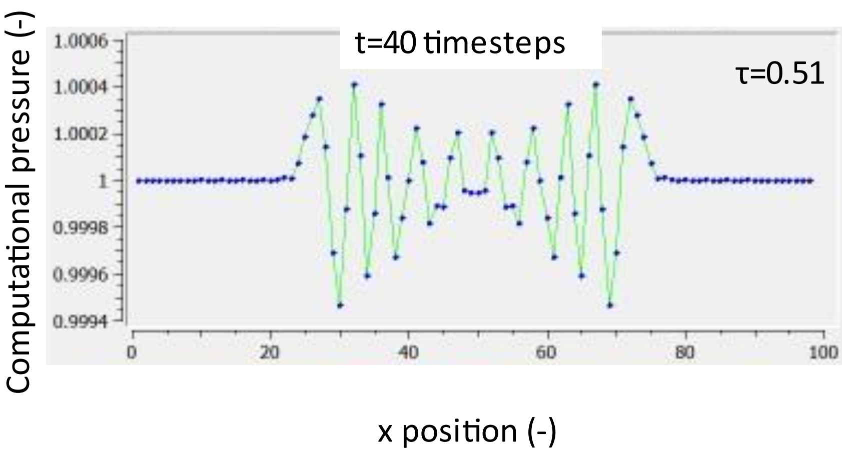


Figure 5: Pulse shape after 40 timesteps, square enclosure (100x100 cells).

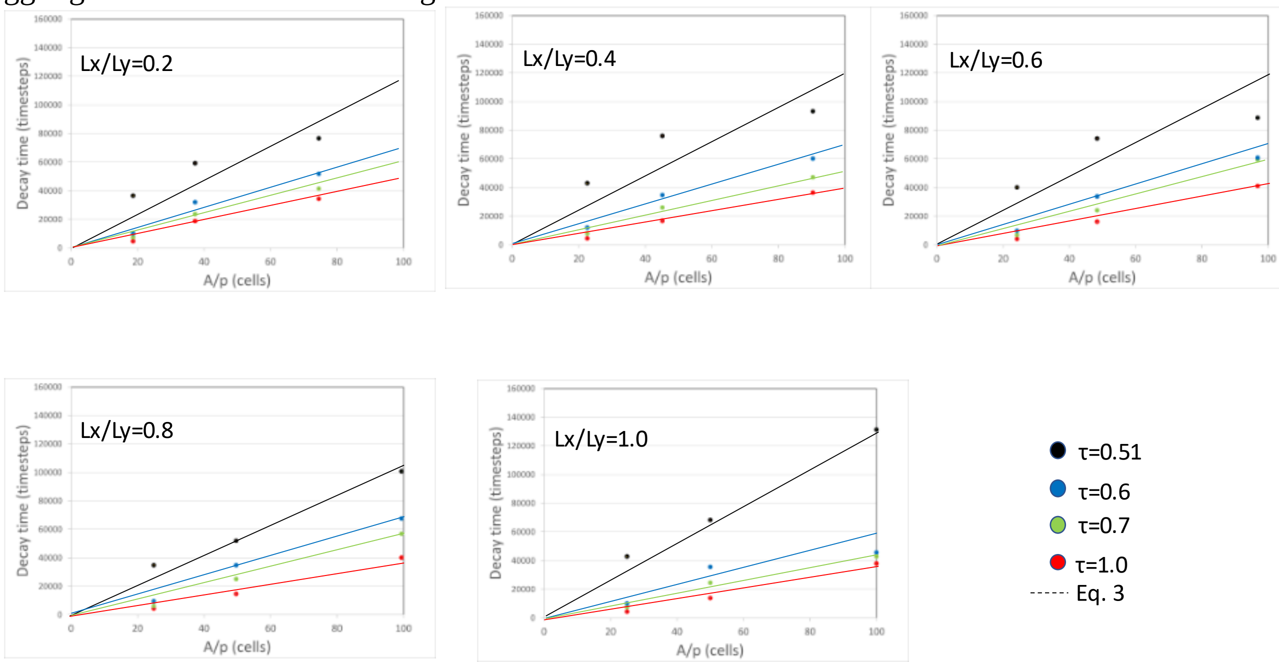
3.2 Shape factor

The reverberation time of a two-dimensional room RT_{xy} can be calculated using the formula represented in Eq. 3 [13-15]:

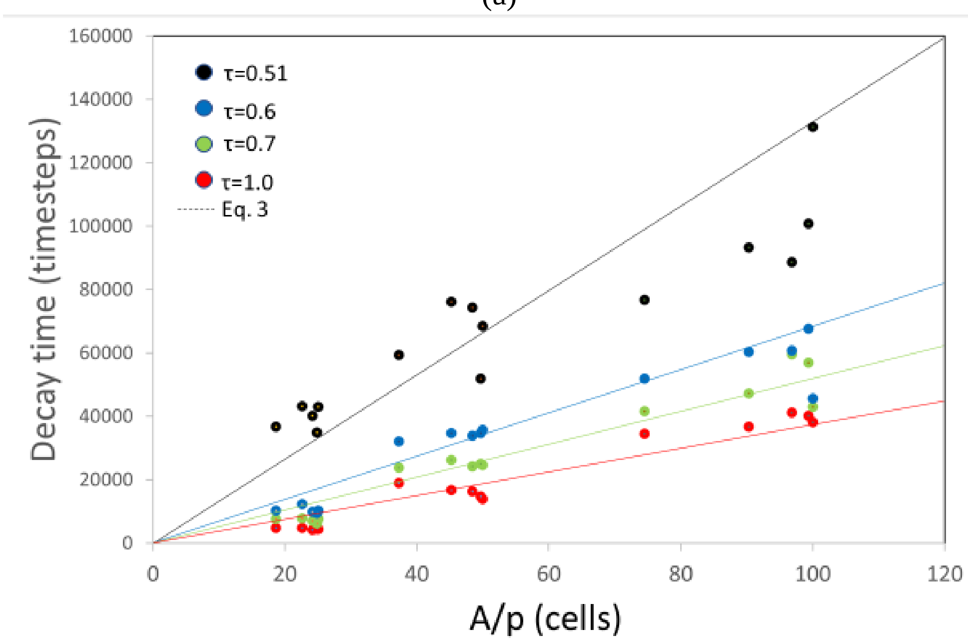
$$RT_{xy} = \frac{0.128}{F(\bar{\alpha}')}\frac{S_{xy}}{L_{xy}} \quad \rightarrow \quad RT_{xy} \propto \frac{S_{xy}}{L_{xy}} \tag{3}$$

This reverberation time is then proportional to the geometrical ratio between the area S_{xy} and the perimeter L_{xy}. On the other hand the average sound absorption coefficient $\bar{\alpha}'$ decreases the RT_{xy}. Neubauer and Koster [15] consider $F(\bar{\alpha}') = -\ln(1-\bar{\alpha}')$; in the present model $\bar{\alpha}'$ was supposed fixed by the selection of the boundary conditions; the applicability of the two-dimensional model to real room acoustic was critically revised by [16].

Figure 6 resumes the results from calculations of the decay time. In the figure, the effect of changing the relaxation time is visible; lower values increase the decay time (less viscous attenuation). The proportionality expressed in Eq. 3 between the decay time and the geometric factor area/perimeter is visible but only describes the main trend. For a given ratio *Lx/Ly* (for example, for squared shapes *Lx/Ly=1* with dimensions 100x100, 200x200, 400x400 and 800x800 cells), the proportionality expressed in Eq.3 can describe the obtained results, bigger is the enclosure bigger is the S_{xy}/L_{xy} ratio and higher is the decay time, Fig. 6 (a). However, this relationship is not clear when the rectangular shape ratio *Lx/Ly* changes, see Fig. 6(b); the main limitation colud be related to a viscous-dominated attenuation even with the lower values of the relaxation parameter considered; future works must explore lower viscosity values using more stable LBM models such as the entropic or the multiple relaxation time models. Some other limitations in the calculations of the decay time could also be linked to this behaviour. The calculations of the envelope and the limits to exclude the early decay of each signal must be optimized in each situation, as well as the total timesteps of the simulations (in this study 20000 timesteps were considered, for all the simulations). In future works, the total time of the simulations will be higher for bigger geometrical domains and signals for more receivers.



(a)



(b)

Figure 6: Decay time vs. shape factor. Comparison with the proportion expressed in Eq.3. (a) fixed rectangular ratio *Lx/Ly* variable area, (b) variable rectangular ratio *Lx/Ly*.

The effect of changing the wall absorption coefficient by adding a porous layer (1cell thickness layer - 50% porosity) near the walls shows a reduction in the decay time (the effect is noticeable for the late decays), see Fig. 7.

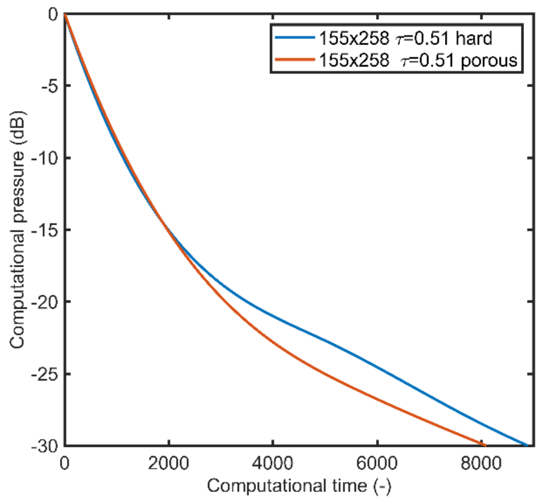


Figure 7: Decay curve, effect of a porous layer near the wall (155x258 cells).

4. Conclusions

The Lattice Boltzmann Method was used to study the propagation of pressure pulses in rectangular enclosures. Circular wavefronts, and symmetric reflection patterns were noted during the simulations, evidencing the great isotropy of the method.

The tuning of the numerical parameters is not straightforward in this numerical method because the time resolution and the spatial resolution are linked by an extra parameter: the relaxation time. Higher is the relaxation time higher is the viscosity and the attenuation of the media. The relaxation parameter must be fixed to lower values; but by this selection, nonlinear instabilities are induced in the solution. The effect of reducing the viscosity in the decay time is notable for all the geometries considered. The geometric ratio (area/perimeter) seems to be directly related to the decay time.

This preliminary study aims to be a first attempt in evaluating the possible applicability of the LBM in room acoustics. However, the effect of porous walls, three-dimensional domains, extinction of stochastic noise, and advanced collision models (that ensure a low viscous attenuation) must be studied in detail to understand the applicability to realistic conditions.

REFERENCES

1. Succi S, Benzi R, Massaioli F. A Review of the Lattice Boltzmann Method, *International Journal of Modern Physics C*, **4**(2), 409-415 (1993).

2. Bocanegra Cifuentes JA, Borelli D, Cammi A, Lomonaco G, Misale M. Lattice Boltzmann Method Applied to Nuclear Reactors—A Systematic Literature Review, *Sustainability*, **12**(18), 7835, (2020). doi:10.3390/su12187835

3. Bocanegra JA, Marchitto A, Misale M. Thermal performance investigation of a mini natural circulation loop for solar PV panel or electronic cooling simulated by lattice Boltzmann method, *International Journal of Energy Production & Management.*, **5**(4), 1-12 (2022). doi:10.2495/EQ-V7-N1-1-12

4. Sharma KV, Straka R, Tavares FW. Current status of Lattice Boltzmann Methods applied to aerodynamic, aeroacoustic, and thermal flows, *Progress in Aerospace Sciences*, **115**, 100616, (2020). doi:10.1016/j.paerosci.2020.100616

5. Marié S, Ricot D, Sagaut P. Accuracy of Lattice Boltzmann Method for Aeroacoustic Simulations, *procedings in 13th AIAA/CEAS Aeroacoustics Conference (28th AIAA Aeroacoustics Conference)*. American Institute of Aeronautics and Astronautics, (2007). doi:10.2514/6.2007-3515

6. Brès G, Pérot F, Freed D. Properties of the Lattice Boltzmann Method for Acoustics, *procedings in 15th AIAA/CEAS Aeroacoustics Conference (30th AIAA Aeroacoustics Conference)*. American Institute of Aeronautics and Astronautics, (2009). doi:10.2514/6.2009-3395

7. Li XM, C. So RM, K. Leung RC. Propagation Speed, Internal Energy, and Direct Aeroacoustics Simulation Using Lattice Boltzmann Method, *AIAA Journal*, **44**(12),2896-2903 (2006). doi:10.2514/1.18933

8. Li XM, K. Leung RC, C. So RM. One-Step Aeroacoustics Simulation Using Lattice Boltzmann Method, *AIAA Journal*, **44**(1), 78-89, (2006). doi:10.2514/1.15993

9. Fu SC, So RMC, Leung RCK. Modeled Boltzmann Equation and Its Application to Direct Aeroacoustic Simulation, *AIAA Journal*, **46**(7), 1651-1662, (2008). doi:10.2514/1.33250

10. Acoustics, measurement of room acoustic parameters. Reverberation time in ordinary rooms, BS EN ISO 3382-2:2008, *British Standards Institution*, London (2012).

11. Komori, F.S. (2015). *LBSim: a fluid dynamics simulator using the lattice Boltzmann method* [Online.] available: https://github.com/fabioskomori/lbsim

12. Bhatnagar PL, Gross EP, Krook M. A Model for Collision Processes in Gases. I. Small Amplitude Processes in Charged and Neutral One-Component Systems, *Phys Rev*., **94**(3), 511-525, (1954). doi:10.1103/PhysRev.94.511

13. Tohyama M, Suzuki A. Reverberation time in an almost-two-dimensional diffuse field, *Journal of Sound and Vibration*, **111**(3):391-398, (1986). doi:10.1016/S0022-460X(86)81400-6

14. Tohyama M. *Sound in the Time Domain*, Springer Singapore, (2018). doi:10.1007/978-981-10-5889-9

15. Neubauer R, Kostek B. Prediction of the reverberation time in rectangular rooms with non-uniformly distributed sound absorption, *Archives of Acoustics*, **26**(3):183-201, (2001).

16. Shalkouhi PJ. Comments on “Reverberation time in an almost-two-dimensional diffuse field” [J. Sound Vib., 111, 391–398, 1986], *Journal of Sound and Vibration*, **333**(13), 2995-2998 (2014). doi:10.1016/j.jsv.2014.02.015