Acoustic and Thermal Correlation for a Building's Envelope in a Mediterranean Climate in Morocco

Rachid Lagtayi*, ***‡, Lamya Lairgi**, Ahmed Khouya***, Abdelmajid Daya**

*Department of Sciences, Industrial and Civil Technologies, Team of sciences and advanced technologies, National School of Applied Sciences, Abdelmalek Essaadi University, Tetouan 2121, Morocco

**Department of Physics, Laboratory of M3ER-, FSTE, Moulay Ismail University, Errachidia 509, Morocco

***Department of Electrical and Industrial Engineering, National School of Applied Sciences, Abdelmalek Essaadi University, Tangier 1818, Morocco

(rachid.lagtayi1@etu.uae.ac.ma , l.lairgi@edu.umi.ac.ma , ahmedkhouya3@yahoo.fr , a.daya@fste.umi.ac.ma)

‡ Corresponding Author: Rachid LAGTAYI, Postal address: National School of Applied Sciences, Abdelmalek Essaadi University, Tetouan 2121, Morocco, Tel: +212 659115006, Email: rachid.lagtayi1@etu.uae.ac.ma

Received: 05.07.2021 Accepted:02.08.2021

Abstract- The aim of this paper is to present a comparative analysis of the thermal and acoustic insulations of four different buildings' envelopes: Single layer clay brick wall (Wall(a)), Single layer concrete brick wall (Wall(b)), double layer hollow brick wall with a medium of polystyrene (Wall(c)) and double layer hollow brick wall with a medium of air (Wall(d)), which are all modelled by using finite element method (FEM) under different climatic conditions. For the steady state, the summer period was chosen on 7th of August 2019 at 2 p.m., while the winter period was opted on 27th of January 2020 at 11 a.m. On the other hand, for the unsteady state, the summer period was chosen from August 1st to 7th, 2019 and the winter period from January 25th to 31st, 2020. Moreover, the study of noise transmission through these walls was released by placing a linear nonmonochromatic source of sound 1m away from the exterior side of each wall and it is emitted sound waves with a velocity of 200 m/s with low frequencies, while an acoustical comparative analysis was investigated by analysing the Sound pressure Level (SPL) variation under the same thermal conditions as done in the two previous steady states study. The results show that the wall (d) is a good thermal and sound insulator compared to the walls (a), (b) and (c) due to the insulation by air gap with a thickness of 0.06 m.

Keywords Thermal insulation, Acoustic insulation, Noise transmission, Sound Pressure Level (SPL)

1. Introduction

Nowadays, developing the building sector has become a very interesting challenge for saving energy, realizing building's comfort, and respecting the safety of our environment. Furthermore, the energy savings becomes a real defiance because of the quick growth of residential buildings and the development of living standards. Thus, the good thermal insulation of the building envelope can regulate the indoor temperature and reduce the energy consumption. Moreover, limiting the inward noise through the buildings' envelope is also needed for realizing simultaneously the thermal and acoustical comfort[1], [2]. In addition, the thermal comfort and the consumed energy of a building depends on its shape, orientation and the thickness of its envelope [3, 7].

In the literature review, many researchers have studied in the last few years various measures to enhance the thermal insulation efficiency of the buildings' envelopes [8, 11]. In 2012, Kou et al [12] has investigated the thermal insulation of polymer-air multilayer (PAM), the results show that by increasing a 6 mm-thick of 4-layers PAM on the indoor side of a glass pane, the energy consumption has reduced by 33% which could be a good solution for energy savings. A paper presented in 2015 by Arıcı and Kan [13] has shown that introducing more air layers in a window is useful for better sealing and insulation performances. In 2019, Araúz et al [14] have studied the impact of the envelope's layout in the thermal behaviour of buildings in Panama, and based on thermal dynamic simulations, the results show that reducing the wall-window ratio (WWR) ratio is highly affected the indoor conditions, but adding insulator layer doesn't improve it. Lairgi et al.[5] have examined the impact of arid climate on the indoor thermal comfort in Errachidia city in Morocco, furthermore they have noted that the insulation by air gap layer is performant, and it acts as a damper of temperature and heat flux. However, the acoustic comfort is crucial, nowadays the attention is focused on the improvement of the noise control efficiency and the provision of the required acoustic comfort because of the increase of the environmental noise, populations density growth, development of industry, transport, and aviation. The living environments are affected by noise from neighbours and its installation from inside the building plus the outdoor low-frequency noise also disturb a lot. However, the overall level of acoustic comfort in contemporary wooden buildings is good enough [15]. The acoustic comfort criterion is strongly dependent on the observer positions, building envelope design and the facades' acoustical properties [16]. Azkorra et al. [17] proved that green walls present a good acoustic insulation, it shows a sound reduction index (Rw) of 15 dB and a weighted sound absorption coefficient (α) of 0.40. Moreover, Thicker materials comparatively have lower air permeability but higher sound absorption properties [18]. The non-woven structure has good sound absorption properties at the mid and higher frequency range, but low sound absorption properties at lower frequencies (100–400 Hz) [19]. Furthermoe, Marques and Pitarma [20] have studied the noise exposure in residential buildings, they have proposed a method which is designed to use open-source technologies and Wi-Fi communication, this system has been tested inside buildings in a continuous form. The results show that the mean sound values range from 41,9 dBA and 46,7 dBA. However, having a simple general correlation between thermal resistance and sound insulation still quite difficult [21]. In fact, Granzotto et al. [22] presented a study on energy and acoustic performances of more than 45 different frame windows and their correlation. the results show by examining of the transmittance Uw, the sound reduction frequency index R and the sound reduction index Rw that the correlation between thermal and acoustical parameters is not possible. Despite this, the correlation will be a good solution for realising simultaneously thermal and acoustical comfort.

The objective of this study is to investigate the correlation between the thermal-acoustic insulations properties of four different buildings' envelopes in Tetouan City which is characterized by a Mediterranean climate. Those envelopes have been modelled and simulated by using finite element method under the same climatic conditions.

2. Material and Methods

2.1. Climate Conditions

In the north of morocco, Tetouan city is characterised by a Mediterranean climate, whereas the summer season is short, warm, humid, arid, and mostly clear and the winter season is long, cold, and partly cloudy. During the year, the temperature generally ranges from 9 °C to 30 °C and is rarely below 5 °C or above 34 °C.

In this study, we have chosen two periods (from 1st to 7th August 2019 and from 25th to 31st January 2020). The climate data conditions were provided by Sania Ramel airport station (Fig.1 and Fig.2). Moreover, according to the Thermal Regulation of Construction in Morocco RTCM, the indoors' air temperature during the winter period was 18°C and it was 25°C during the summer period.

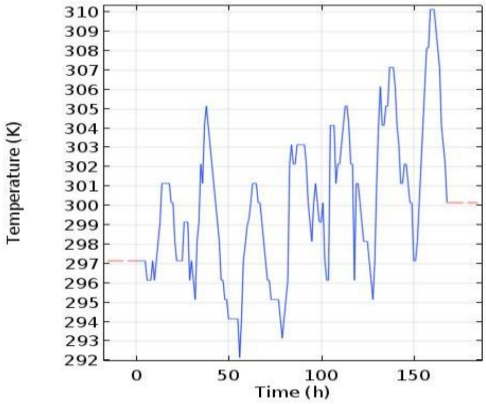


Fig. 1. Hourly measured temperature from August 1st to 7th, 2019.

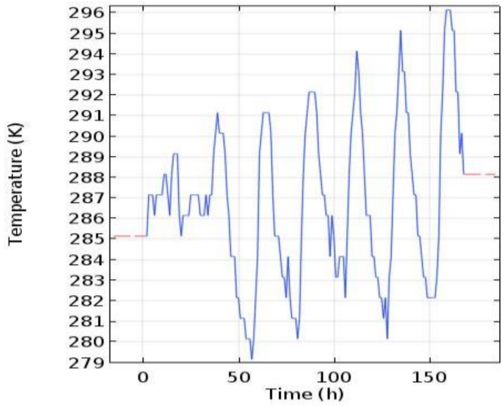


Fig. 2. Hourly measured temperature from January 25th to 31st, 2020.

2.2. Thermal Model Description

Figure 3 shows the four buildings envelopes mostly used for residential in Tetouan city which are: a single layer of hollow clay brick wall (Wall(a)), a single layer of hollow concrete brick wall (Wall(b)), double layers of hollow clay brick wall with a medium of polystyrene (Wall(c)), and double layers of hollow brick wall with a medium of air gap (Wall(d)).

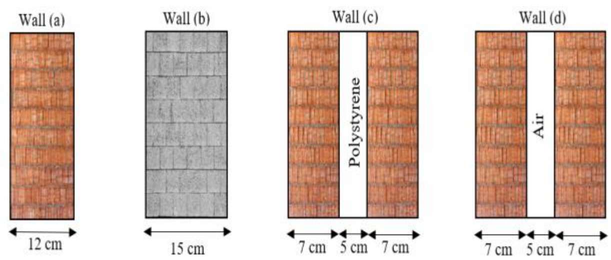


Fig.3. The four various buildings envelopes under study.

Table 1 presents the thermo-physical properties of the four different buildings' envelopes under study.

Table 1. Thermo-physical properties of the walls (a), (b), (c) and (d)

Building's Envelope type	Wall compositions	Thickness (m)	K (W/m.k)	Cp (J/Kg.k)	ρ (Kg/m3)
(a)	**Dried clay**	0.12	0.915	790	720
(b)	**Concrete**	0.15	2.1	800	2400
(c)	**Dried clay**	0.07	0.915	790	720
	Polysterene (medium)	0.05	0.04	1450	34
	Dried clay	0.07	0.915	790	720
(d)	**Dried clay**	0.07	0.915	790	720
	Air (medium)	0.5	0.023	1004	1.3
	Dried clay	0.07	0.915	790	720

The studied buildings' envelopes are considered as the borders between the indoor and the outdoor environments, While, for studying these various thermal insulators, a discretization of the domain is required for Finite Element Method (FEM) by meshing it to have nodal representation geometry and functional representation of each wall layer. Furthermore, this method is heavily mesh dependent, while refining is needed for a geometrical and mathematical reasons, whereas the mesh refinement mainly affects the precision of results. Consequently, our simulations are performed by using a 3088-elements triangular mesh which represents a high precision of our modelisation (Fig.4).

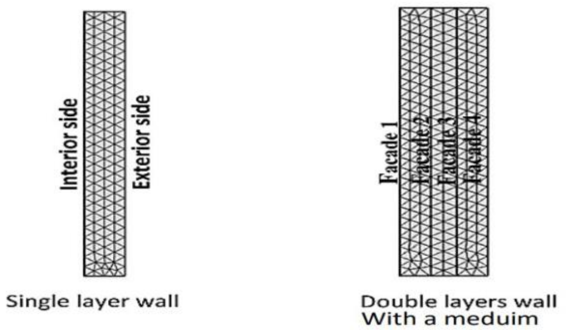


Fig.4. Triangular mesh generation (3088 elements).

In our thermal model, the heat transfer through the walls (a), (b), (c) and (d) is induced by conduction and convection as it's presented in the Figure 5 at below. Moreover, the wall's left side is exposed to the ambient air, while its interior temperature Tint is maintained constant. A convective heat transfer is occurred between the interior facade and ambient air. The wall's right side is opened to a periodic outdoor ambient air temperature Text (Fig.1 and Fig.2). Furthermore, a convective and radiative conditions are established inside and outside the wall, and it is translated by global coefficients hext and hint.

This study is done under the following boundary conditions:

- In case of the double layer walls (b) and (c), the thermal contact resistance between the interior facades and the insulators is assumed to be perfect.

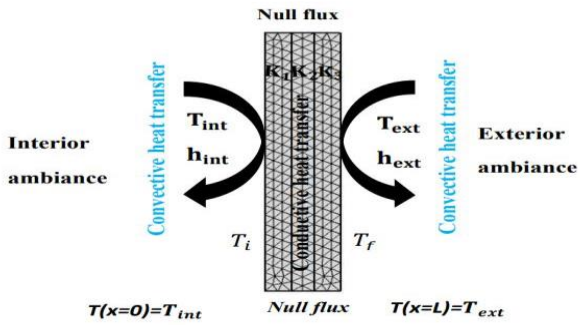


Fig.5. Boundary conditions of thermal model

- The variation of thermal and physical properties is negligible.
- An adiabatic condition is assumed at the horizontal's sides of the wall.
- Perfect contact between the layers; therefore, the interface resistance is Negligible.

For the stationary regime, the temperature is independent of time and the general governing equation is presented as:

$$e\rho C_p U.\nabla T + \nabla.q = eQ + q_0 + eQ_{ted} \quad (1)$$

The conductive heat flux is determined by:

$$q = -eK\nabla T \quad (2)$$

The convective heat is given by:

$$q_0 = h(T_{int} - T_{ext}) \quad (3)$$

The term eρCpU.∇T is null due to the absence of translational motion in our models plus the heat flux of additional heat sources eQ=0 because no additional sources have been taken into account.

The governing equation (1) during stationary models becomes as:

$$-eK\nabla^2 T = h(T_{int} - T_{ext}) \qquad (4)$$

For the transitional regime, the temperature is dependent of time and the heat transfer equation is defined as:

$$\rho C_p \frac{\delta T}{\delta t} = K\nabla^2 T \qquad (5)$$

2.3. Acoustics Model Description

For the acoustics conditions, a linear nonmonochromatic source of sound was placed at 1m far from the exterior side of each wall and it is emitted sound waves toward the tested borders with an inward velocity of 200 m s and low frequencies range between [100Hz – 200Hz]. The speed of sound across the building materials is the distance that sound waves travel in a given amount of time which is dependent on the density of materials and the atmosphere temperature conditions. The speed of sound in solids V (Table 2) is strongly dependent on their density and it's determined by:

$$V = \sqrt{\frac{B}{\rho}}\,. \qquad (6)$$

where, B is the bulk modulus (Pa) and ρ is the material density (kg/m²).

Figure 6 presents our proposed model for studying various acoustic insulators as it is shown at below:

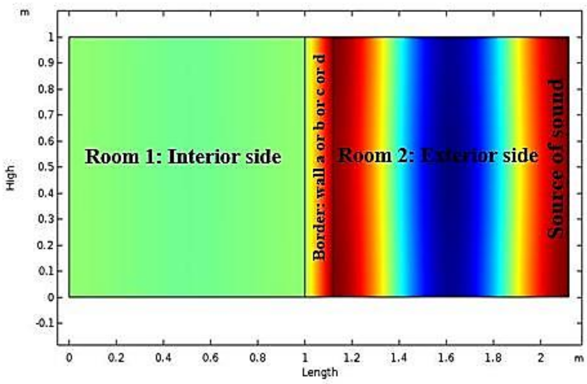


Fig. 6. Acoustic proposed model

Table 2. Acoustic properties of different solid layers of the walls(a), (b), (c) and (d).

Building Envelope type	Bulk Modulus (Pa)	Speed of sound V (m/s)
(a)	9.33×10^9	3600
(b)	2.45×10^{10}	3200
(c)	9.33×10^9	3600
	4.26×10^7	1120
	9.33×10^9	3600
(d)	9.33×10^9	3600
	(Table 2)	(Table 2)
	9.33×10^9	3600

The table 2 presents the acoustical properties of the four buildings' envelopes which are mostly built as exterior buildings' walls in Tetouan region.

Table 3 presents the speed of sound of air C which is depending on the outside and inside atmosphere temperatures, and it's determined by:

$$C = 313 + (0.6\times T). \qquad (7)$$

Where T is the temperature in °C.

Table 3. Speed of sound through the air-gap under different thermal conditions.

Air-gap	Temperature in °C	Speed of sound C (m/s)
1st case	37	353.2
2nd case	32.85	350.71
3th case	26	346
4th case	18	341.8
5th case	13.3	338.98
6th case	11	337.6

The variations of the Sound Pressure Level (dB) through the walls (a), (b), (c) and (d) are determined by:

$$SPL = 20\log_{10}\left(\frac{P}{P_{ref}}\right) \qquad (8)$$

where, P is the sound pressure (Pa) and P_{ref} is the reference pressure.

($P_{ref} = 20.\ 10^{-6}$ Pa)

3. 3. Results and Discussions

3.1. Thermal Study

3.1.1. Stationary Regime

The following figures present the temperature's variations through the walls (a), (b), (c) and (d) of different thicknesses on the 7th of August 2019 at 2 p.m. (Fig.7) and on the 27th of January 2020 at 11 a.m. (Fig.8). We note that the wall (d) shows a good thermal resistance compared to the other studied walls. In fact, the temperature reduced from 34.80°C in the outside to 23.45°C inside in the summer period (Fig.7), and it kept warm inside in the winter (Fig.8) with 15.85°C despite 8.85°C in the outside due to the insulation by air gap with a thickness of 0.06 m, which reveals a good capacity of air gap to block heat dissipation during summer and conserve the inside warm during the winter season, furthermore, this result is similar to others found by researchers [5], [23].

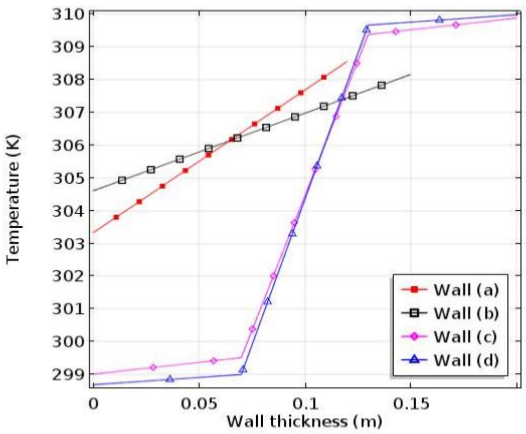


Fig.7. Temperature changes in terms of the walls' (a), (b), (c) and (d) thicknesses on the 7th of August 2019 at 2 p.m.

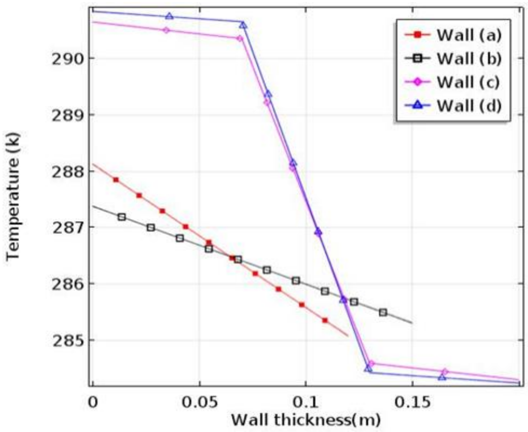


Fig. 8. Temperature changes in terms of the walls' (a), (b), (c) and (d) thicknesses on the 27th of January 2020 at 11 a.m.

3.1.2. Transitional Regime

3.1.2.1. Summer Period

Figures 9, 10, 11 and 12 present the heat transfer changes at the different sides of the walls (a), (b), (c) and (d) during a summer week from 1st to 7th August 2019 in Tetouan city.

In the figures 9 and 10, we note that the temperature's changes at the internal and at the external sides of the wall waves in the same manner with different values. Indeed, the exterior sides of the walls (a) and (b) reaches successively a maximum temperature of 34.85°C and 33.55°C, while their interior sides reach successively a maximum temperature of 29.85°C and 29,35°C. Those values show that the heat transfer through the walls (a) is reduced by 14.3% while for the wall (b) is reduced by 12.5%. Which divulge that the thermal inertia of the single layer of hollow concrete brick wall is significant compared to the single layer of hollow clay brick one due to its capacity to store heat during the day and restore it at night.

Figures 11 and 12 show that at the exterior layers of walls (d) and (c), the temperature reaches approximatively the same maximum measure of 35,80°C. However, at their interior layers, the temperature has decreased, and it periodically changes between 20.05°C and 27.85°C for the wall (c), which leads to a heat block with a rate of 22.21% due to the thermal insulation by polystyrene. And it varies between 19.85°C and 26.65°C for the wall (d) due to the thermal insulation by air gap between the inner and the outer layers, which disclose that the air gap prevents the heat to penetrate towards the inside.

These results confirmed that the thermal insulation with an air gap of 6 cm, still a good choice for buildings' envelopes in Tetouan's climate compared to the other walls under study, plus it helps to reduce materials' costs. These results have been validated by other researchers [23], [24].

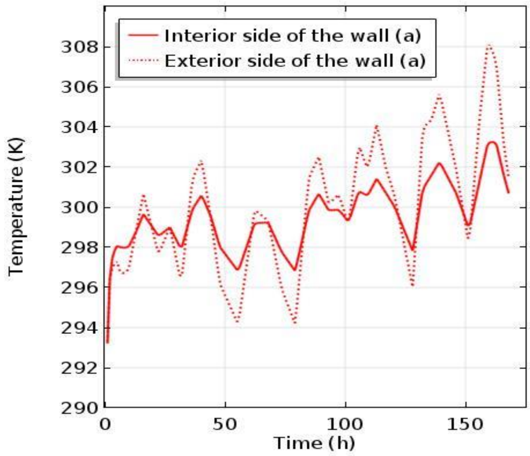


Fig. 9. Temperature changes between the inner and the outer facades of the wall(a).

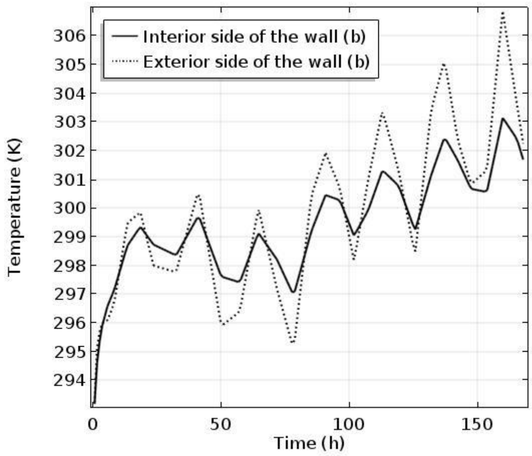


Fig. 10. Temperature changes between the inner and the outer facades of the wall (b).

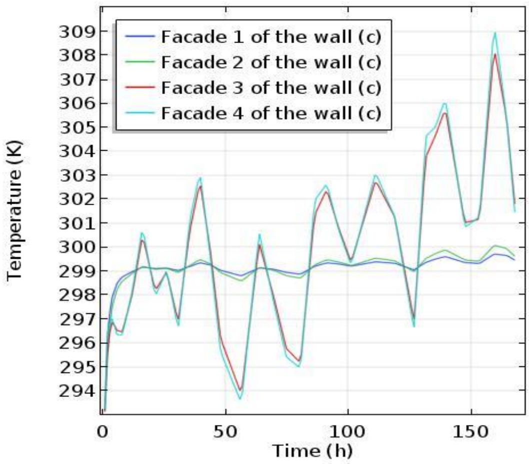


Fig. 11. Temperature changes between the inner and the outer facades of the wall (c).

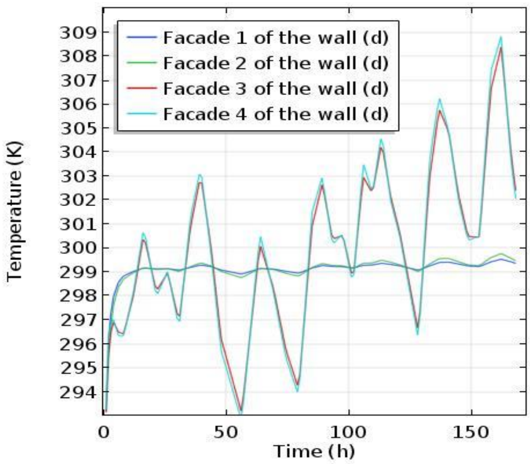


Fig. 12. Temperature changes between the inner and the outer facades of the wall (d).

Figures 13, 14, 15 and 16 present successively the conductive heat flux variation through the walls (a), (b), (c) and (d) at four times per day, 8a.m., 13 p.m., 20 p.m. and 00: 00 a.m.

We observe that the heat flux through the wall (b) reaches the maximum value of 30W/m² on its exterior side at 13 p.m. then it starts decreasing linearly from the outside facade towards the interior facade, because of its biggest thermal inertia compared to the other studied walls, which gives it the capacity to store and restore heat between the indoor and the outdoor environments. However, its thermal resistance is the lowest one in comparison with the other walls. Furthermore, the heat flux's variations through the walls (c) and (d) during the different daily studied moments (8a.m., 13p.m., 20 p.m. and 00:00 a.m.) still reaching the minimum heat flux values at the walls' external facade which vary at a range of 4.8 W/m² for the wall (c) and 4.9 W/m² for the wall (d) and it decreased very slightly between 5 W/m² and 0.1 W/m². These results prove that their thermal resistance efficiency is approximatively similar, and they have a good ability to reduce and block the heat flux trough. However, the thermal insulation by air gap is still the best choice in comparison with the rest of the studied buildings envelops for retaining cooling during summer with a less materials and energy consumption.

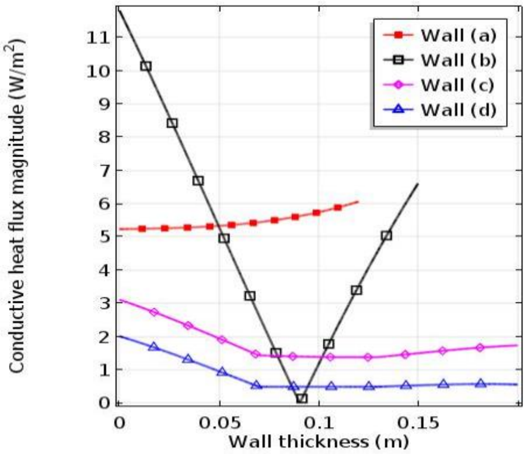


Fig. 13. Conductive heat flux through the walls (a), (b), (c) and (d) at 8 a.m. in terms of the walls' thicknesses.

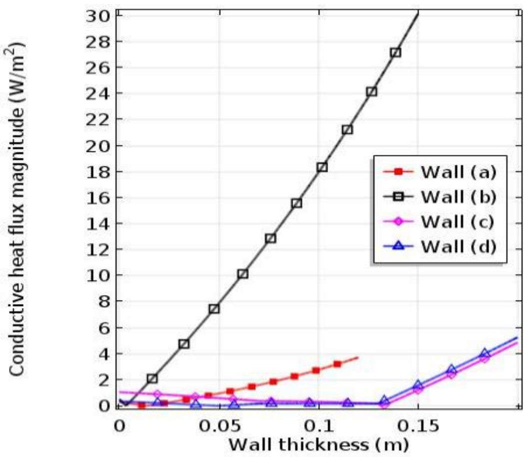


Fig. 14. Conductive heat flux through the walls (a), (b), (c) and (d) at 13p.m in terms of the walls' thicknesses.

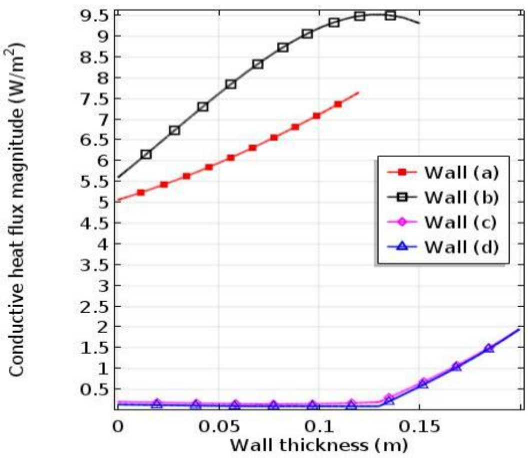


Fig. 15. Conductive heat flux through the walls (a),(b),(c) and (d) at 20 p.m in terms of the walls' thicknesses.

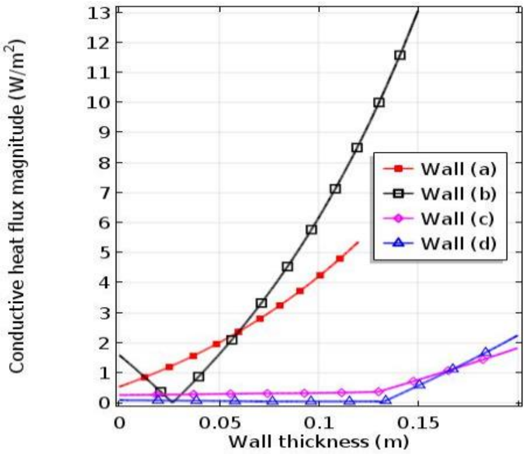


Fig. 16. Conductive heat flux through the walls (a), (b), (c) and (d) at 00:00 a.m. in terms of the walls' thicknesses.

3.1.2.2. Winter Period

Figures 17, 18, 19 and 20 present the heat transfer variations at the different facades of the walls (a), (b), (c) and (d) for a winter week between the 25th and 31st January 2020.

The results show that the temperature at the outer facade of the wall (a) reaches a minimum of 8.65°C, while the temperature at its inner facade achieves a minimum of 13.75°C. Which reveals that the wall (a) blocks heat to exit towards the outside with a rate of 37.1%. While, for the wall (b) the minimums of temperatures at its outer facade and at its inner facade reaches respectively 10.35°C and 13.35°C. Which leads to a heat conservation inside the building of 22.42%. Although this, we observe that the temperature at the inner facades of the walls (a) and (b) is highly affected in parallel with the outside temperature atmosphere changes because of the absence of the thermal insulation and their weak thermal resistance.

Moreover, the temperature at the exterior layer of the wall (c) (Fig.19) changes between a minimum of 4.85°C and a maximum temperature of 19.45°C, while at the interior layer it varies between a minimum of 14.85°C and a maximum of 17.85°C (Fig.20), which shown that insulation by polystyrene prevent heat to exit across the outside with a rate of 67.35%. Whereas, for the wall (d) the temperature at its exterior layer waves between a minimum of 4.65°C and a maximum of 20.75°C, while at its interior layer it changes between a minimum of 15.75°C and a maximum of 17.85°C, which proved that the air gap insulator is highly recommended in winter due to its capacity to keep inside warmer with a rate of 70.48%.

These results prove that insulation by air gap has given a good capacity to the wall (d) to reduce and block heat transfer during the winter season, which confirmed that the thermal insulation by air gap with a thickness of 6 cm is good enough compared to the insulation by polystyrene. These results have previously been highlighted by other recent research [5], [24] .

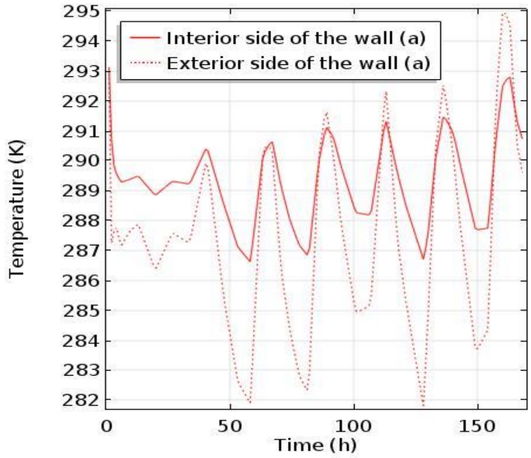


Fig. 17. Temperature changes between the inside and the outside facades of the wall (a).

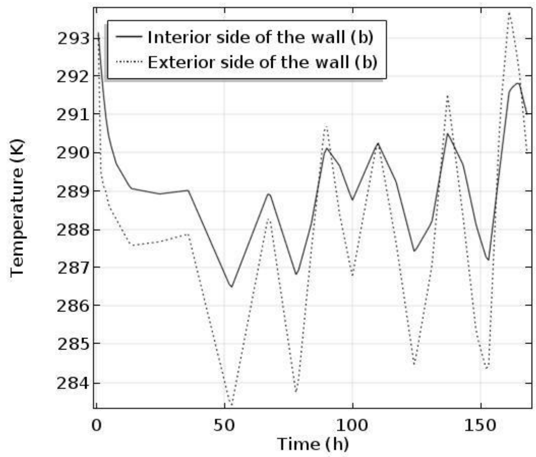


Fig. 18. Temperature changes between the inside and the outside facades of the wall (b).

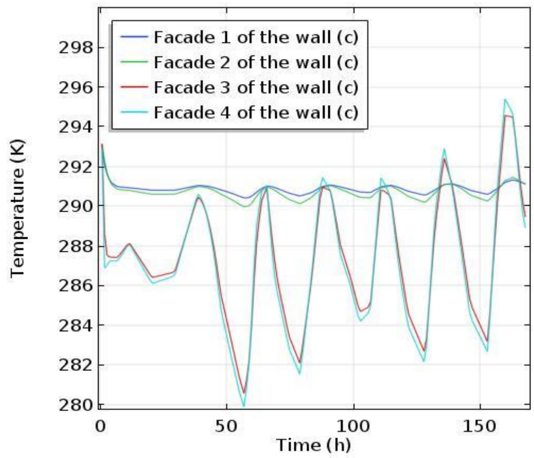


Fig. 19. Temperature changes between the inside and the outside facades of the wall (c).

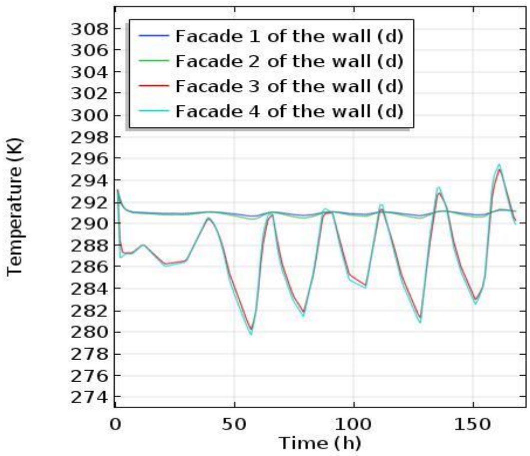


Fig. 20. Temperature changes between the inside and the outside facades of the wall (d).

The figures 21, 22, 23 and 24 show the heat flux changes through the walls (a), (b), (c) and (d) during a winter week (from 25th January to 31st, 2020) at four times per day, 8a.m., 13 p.m., 20 p.m. and 00: 00 a.m.

We observe that the heat flux through the walls (a) and (b) is higher compared to that shown across the walls (c) and (d) at the daily four times studied. And it is almost constant for the two walls (c) and (d) due to the insulation's layer. Whereas the heat flux through the wall (d) is the lowest with a value of 1.5 W/m² in comparison with the other walls under study. It has shown a good capacity to reduce heat flux through it due to the insulation by air gap with a thickness of 6 cm.

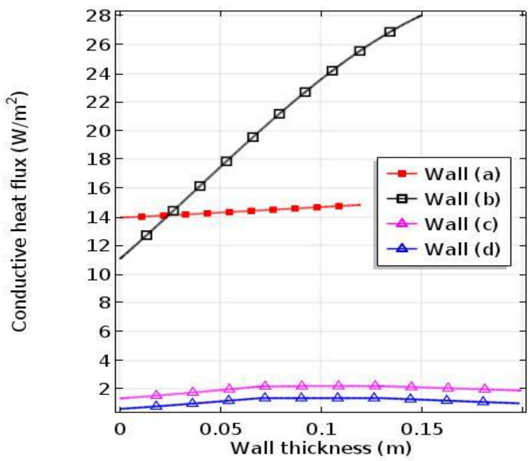


Fig. 20. Conductive heat flux through the walls (a), (b), (c) and (d) at 8 a.m in terms of the walls' thicknesses

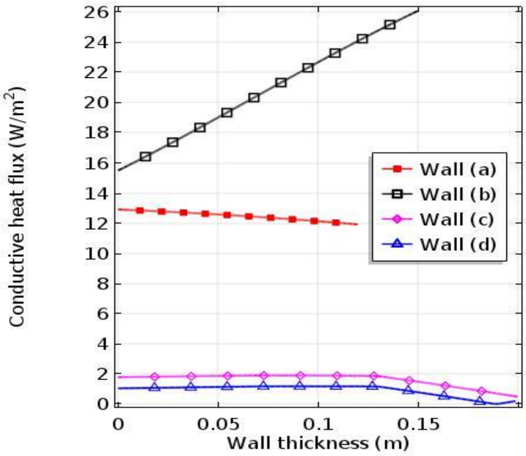


Fig. 21. Conductive heat flux through the walls (a), (b), (c) and (d) at 13p.m in terms of the walls' thicknesses.

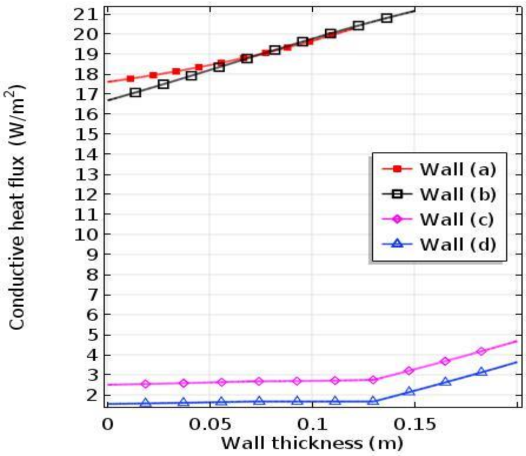


Fig. 23. Conductive heat flux through the walls (a), (b), (c) and (d) at 20 p.m. in terms of the walls' thicknesses.

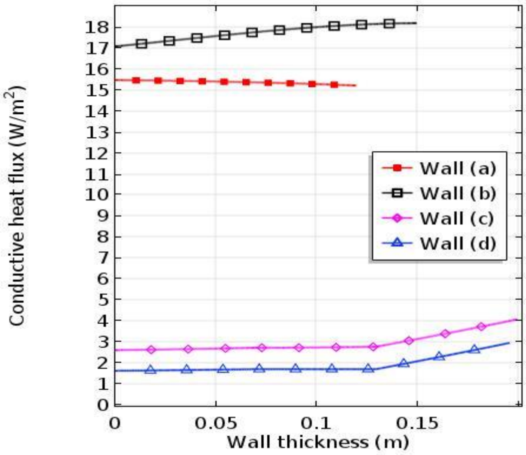
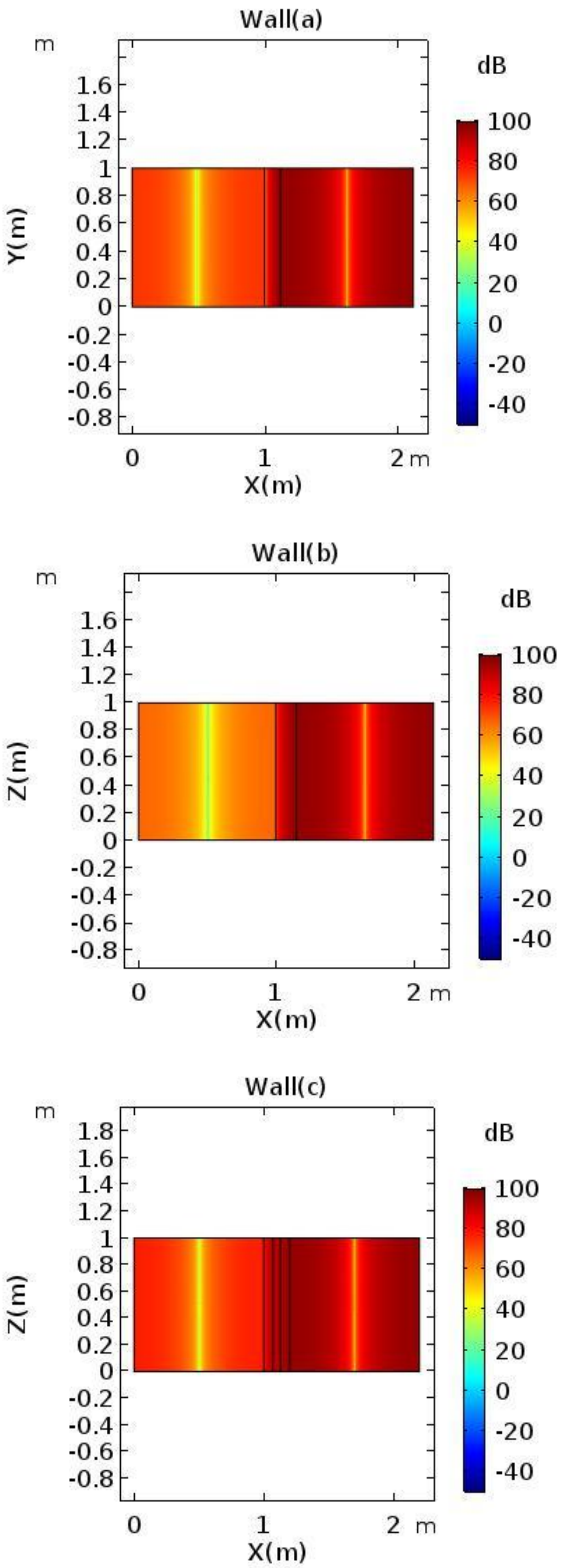


Fig. 24. Conductive heat flux through the walls (a), (b), (c) and (d) at 00:00 a.m. in terms of the walls' thicknesses.

3.2. Acoustic Study

The figure 25 presents the acoustical radiations of sound pressure transmission across the walls (a), (b), (c) and (d) between the room 1 and 2 (Fig.6).



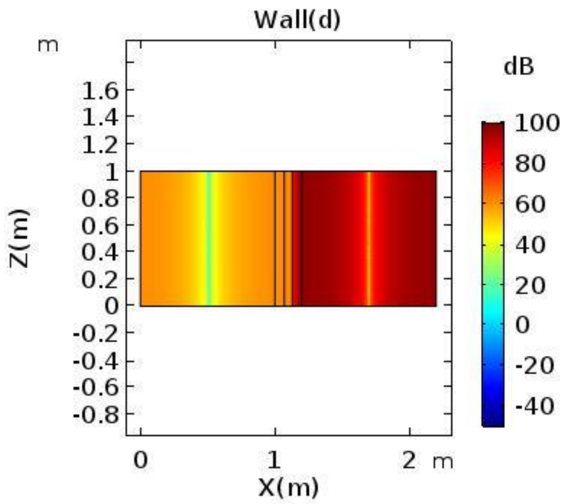


Fig. 25. Acoustic radiations' pressure through the walls (a), (b), (c) and (d).

The figures 26 and 27 present the variation of the sound pressure level when the sound waves cross the walls (a), (b), (c) and (d) during summer and winter seasons. We can note that before the sound waves arrive to the borders, the sound pressure level reaches a maximum of 98 dB but when the sound waves cross borders (walls (a) or (b) or (c) or (d)) the sound pressure level decreases quickly and reaches different values which are dependent on each wall's acoustical properties.

In the summer season (Fig.26), the sound pressure level is reduced by 20.4% for the wall (a), 21.4% for the wall (c), 31.6% for the wall (b) and 36.7% for the wall (d). While in the winter season (Fig.27) the sound pressure level is reduced by 25.5% for the wall (a), 27.6% for the wall (c), 38.8% for the wall (b) and 67.3% for the wall (d). Which reveals that the wall (d) presents the highest rate of sound attenuation for the two periods compared to other walls under study. The walls (a) and (c) are characterized by the lowest rate of sound pressure attenuation in comparison with the other walls, because the wall (a) is thin compared to other walls and the wall (c) isn't homogenous compared to the walls (b) and (d). In addition to that, the rate of sound pressure level attenuation of the wall (c) during summer (Fig. 8) is less than that shown during winter season (Fig. 9) which means that temperature has also an impact on the soundproofing performances.

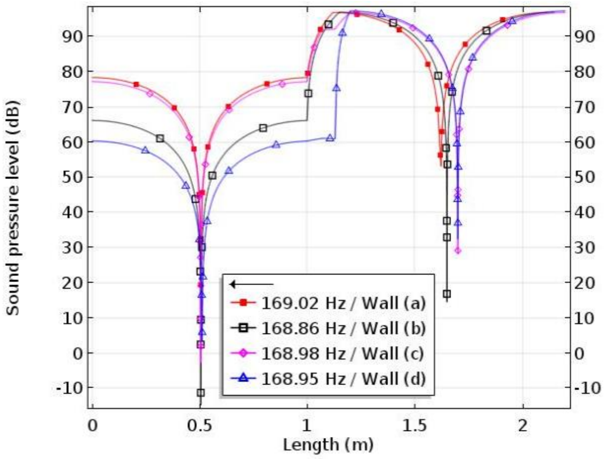


Fig. 26. Sound pressure Level variation across different acoustical insulators (walls a, b, c and d) during summer season.

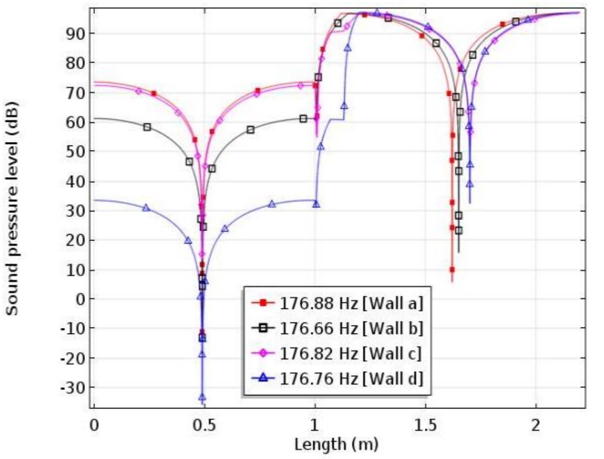


Fig. 27. Sound pressure Level variation across different acoustical insulators (walls a, b, c and d) during winter season.

4. Conclusion

In this paper, we have presented a comparative study of the thermal and acoustical insulations of four different buildings' envelopes: Single layer clay brick wall (Wall(a)), Single layer concrete brick wall (Wall(b)), double layer hollow brick wall with a medium of polystyrene (Wall(c)) and double layer hollow brick wall with a medium of air (Wall(d)). The obtained results show that the walls (a) and (b) are characterized by a weak thermal resistance compared to the other walls (c) and (d), due to the absence of the thermal insulation. However, the rate of sound attenuation of the wall (b) still better than that shown by the walls (a) and (c). Whereas, the wall (d) is an efficient thermal-acoustic insulator compared to the walls (a), (b) and (c) due to its insulation by air gap with a thickness of 0.06m. Based on these results, we deduce that despite the adequate thermal resistance of certain buildings' envelopes, their acoustic insulation performances could be very weak, which could negatively influence the acoustical comfort of inhabitants.

Finally, the correlation between thermal and acoustical insulation properties still quite difficult but researching for special correlated models for homogenous and thicker walls of similar structure is possible.

Acknowledgements

We would like to thank every single author for her/his contribution to achieve this work.

References

[1] C. Zou, R. Zhu, Z. Tao, D. Ouyang, and Y. Chen, "Evaluation of Building Construction-Induced Noise and Vibration Impact on Residents," *Sustainability*, vol. 12, no. 4, p. 1579, February 2020.

[2] P. Ricciardi and C. Buratti, "Environmental quality of university classrooms: Subjective and objective evaluation of the thermal, acoustic, and lighting comfort conditions," *Building and Environment*, vol. 127, pp. 23–36, January 2018.

[3] S. Pathirana, A. Rodrigo, and R. Halwatura, "Effect of building shape, orientation, window to wall ratios and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate," *International Journal of Energy and Environmental Engineering*, vol. 10, no. 1, pp. 107–120, January 2019.

[4] H. Alhaidary, A. K. Al-Tamimi, and H. Al-Wakil, "The combined use of BIM, IR thermography and HFS for energy modelling of existing buildings and minimising heat gain through the building envelope: a case-study from a UAE building," *Advances in Building Energy Research*, pp. 1–24, December 2019.

[5] L. Lairgi, R. Lagtayi, A. Daya, R. Elotmani, and M. Touzani, "The Impact of Arid Climate on the Indoor Thermal Comfort in the South-East of Morocco," *International Journal of Photoenergy*, vol. 2021, p. 15, August 2021.

[6] G. Nalcaci and G. Nalcaci, "Modeling and Implementation of an Adaptive Facade Design for Energy Efficiently Buildings Based Biomimicry," in *8th International Conference on Smart Grid, icSmartGrid 2020*, 2020, pp. 140–145, 17-19 June 2020.

[7] I. Alsurakji, R. Abdallah, M. Assad, and A. El-Qanni, "Energy Savings and Optimum Insulation Thickness in External Walls in Palestinian Buildings," in *2021 12th International Renewable Engineering Conference, IREC 2021*, 2021, pp. 1–5, 14-15 April 2021

[8] D. Shi, J. Wang, and W. Deng, "Smart Building and Construction Materials," *Advances in Materials Science and Engineering*, vol. 2019, p. 2432915, January 2019

[9] P. Krause, A. Nowoświat, and K. Pawłowski, "The impact of internal insulation on heat transport through

the wall: Case study," *Applied Sciences (Switzerland)*, vol. 10, no. 21, pp. 1–18, October 2020

[10] K. Kant, A. Shukla, and A. Sharma, "Heat transfer studies of building brick containing phase change materials," *Solar Energy*, vol. 155, pp. 1233–1242, October 2017.

[11] G. Gao, J. Li, and Y. Wen, "DeepComfort: Energy-Efficient Thermal Comfort Control in Buildings Via Reinforcement Learning," *IEEE Internet of Things Journal*, vol. 7, no. 9, pp. 8472–8484, January 2020.

[12] R. Kou, Y. Zhong, Q. Wang, J. Kim, R. Chen, and Y. Qiao, "Improved window energy efficiency with thermal insulating polymer-air multilayer," *Applied Thermal Engineering*, vol. 191, p. 116890, June 2021.

[13] M. Arıcı and M. Kan, "An investigation of flow and conjugate heat transfer in multiple pane windows with respect to gap width, emissivity and gas filling," *Renewable Energy*, vol. 75, pp. 249–256, March 2015.

[14] J. Araúz, D. Mora, and M. C. Austin, "Impact of the envelope layout in the thermal behavior of buildings in Panama: A numerical study," in *Proceedings - 2019 7th International Engineering, Sciences and Technology Conference, IESTEC 2019*, 2019, pp. 209–214, 9-11 Oct. 2019.

[15] D. Bard, N.-G. Vardaxis, and E. Sondergard, "Acoustic Comfort Investigation in Residential Timber Buildings in Sweden," *J. Sustain. Archit. Civ. Eng*, vol. 1, pp. 78–89, 2019.

[16] A. Taghipour, S. Athari, A. Gisladottir, T. Sievers, and K. Eggenschwiler, "Room Acoustical Parameters as Predictors of Acoustic Comfort in Outdoor Spaces of Housing Complexes," *Frontiers in Psychology*, vol. 11, p. 17, March 2020.

[17] Z. Azkorra *et al.*, "Evaluation of green walls as a passive acoustic insulation system for buildings," *Applied Acoustics*, vol. 89, pp. 46–56, March 2015.

[18] M. Küçük and Y. Korkmaz, "The effect of physical parameters on sound absorption properties of natural fiber mixed nonwoven composites," *Textile Research Journal*, vol. 82, no. 20, pp. 2043–2053, May 2012.

[19] H. S. Seddeq, N. M. Aly, A. Marwa A, and M. H. Elshakankery, "Investigation on sound absorption properties for recycled fibrous materials," *Journal of Industrial Textiles*, vol. 43, no. 1, pp. 56–73, 2013.

[20] G. Marques and R. Pitarma, "Noise Exposure in Residential Buildings: An Internet of Things Approach for Enhanced Acoustic Comfort and Occupational Health," in *2020 15th Iberian Conference on Information Systems and Technologies (CISTI)*, 2020, pp. 1–6, 24-27 June 2020.

[21] J. Nurzyński, "Is thermal resistance correlated with sound insulation?," *Energy Procedia*, vol. 78, pp. 152–157, November 2015.

[22] N. Granzottoa, F. Bettarellob, A. Ferlugac,L. Marsichc,C. Schmidc,P. Faustid, M. Caniatocd, "Energy and acoustic performances of windows and their correlation," *Energy and Buildings*, vol. 136, pp. 189–198, February 2017.

[23] M. Boukendil, A. Abdelbaki, and Z. Zrikem, "Numerical simulation of coupled heat transfer through double hollow brick walls: Effects of mortar joint thickness and emissivity," *Applied Thermal Engineering*, vol. 125, pp. 1228–1238, October 2017.

[24] B. Jamal, M. Boukendil, A. Abdelbaki, and Z. Zrikem, "Numerical simulation of coupled heat transfer through double solid walls separated by an air layer," *International Journal of Thermal Sciences*, vol. 156, no. April, p. 106461, October 2020.