International Science and Technology Journal
المجلة الدولية للعلوم والتقنية

عدد خاص بالمؤتمر الليبي الدولي للعلوم التطبيقية و الهندسية دورته الثانية
LICASE -2
2024 / 10 / 30-29

المجلة الدولية للعلوم والتقنية
International Science and Technology Journal
ISTJ

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Numerical Simulation and Scrutinizing the Influence of Common Materials Trombe Wall on the Air Gap Region

http://www.doi.org/10.62341/ogma1124

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Abstract

The study delves into an investigation of the influence of diverse common materials on the performance of conventional Trombe walls, namely concrete, cement, and brick. To accomplish that, the utilization of two-dimensional computational fluid dynamics **(CFD)** simulations with ANSYS Fluent was done to profoundly analyze the air gap region and map out the temperature distributions and air dynamics. The accumulating of beneficial understandings from the findings will significantly contribute to the optimization of Trombe wall designs, thereby enhancing energy efficiency and proposing practical guidance for sustainable building practices. Pushing onwards, Recommendations for future research could potentially incorporate three-dimensional **CFD** simulations for a more comprehensive understanding, also examining a broader array of material alternatives and additionally fine-tuning the design parameters precisely within the air gap region.

Keywords: Renewable Energy, Trombe Wall, Solar Energy, 2D Simulation, CFD

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المحاكاة والفحص الدقيق لتأثير المواد الشائعة في بناء جدار ترامب على منطقة الفجوة الهوائية

عمر ابشيش، جمال ماشينة، منذر البشتي، أكرم موسى

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الملخص

الدراسة تبحث في تأثير المواد المتاحة على أداء جدران الترامب التقليدية، كالخرسانة والإسمنت والطوب. ولتحقيق ذلك، تم استخدام عمليات المحاكاة الحاسوبية ذات البعدين باستخدام برنامج محاكاة الموائع انسيس فلونت لتحليل منطقة فجوة الهواء التي بين الجدار والزجاج تحليلاً عميقاً والخروج بمخططات لتوزيع درجات الحرارة وحركة الهواء. وستسهم النتائج التي تحصل عليها إسهاما كبيرا في تحقيق الاستفادة المثلى من تصاميم جدار ترامب، مما يعزز كفاءة الطاقة ويقترح توجيهات وارشادات للبناء المستدام. وبالمضي قدماً، يمكن أن تشمل التوصيات المتعلقة بالبحوث المستقبلية عمليات محاكاة ثلاثية الأبعاد من أجل فهم أكثر شمولاً، كما يمكن البحث في مجموعة أوسع من المواد البديلة الاخرى، وكذلك دراسة متغيرات التصميم داخل منطقة فجوة الهواء.

الكلمات المفتاحية: الطاقة المتجددة، جدار ترامب ، الطاقة الشمسية ، محاكاة ثنائية الابعاد ، محاكاة لحركة الموائع

Introduction

With the emergence of the present technological era and the continuous advancement in all scientific fields, the demand for energy rises exponentially as the era progresses, leading to the exploration of new energy sources. Renewable energy sources such as solar energy hold tremendous potential in all engineering fields, specifically for heating and cooling systems that assist in providing cozy temperatures during all-year seasons. The adaptation of such systems that exploit nature for energy production is not the sole essential benefit but also has friendly aspects for the environment and all creatures on planet Earth.

The French architects Felix Trombe and Jacques Michel in the late **1960s** developed a passive solar heating system known as the Trombe Wall, which has gained significant popularity for its prospect of enhancing energy efficiency in structures, mainly in cold environments **[1]**. This innovative system utilizes a south-facing wall constructed of materials with high thermal mass covered with glazing, its functional principle is straightforward yet effective: solar radiation infiltrates the glazing, heats the massive wall, and subsequently heats the air in the adjacent room via radiation and convection **[2] [3]**.

An enormous amount of studies have been done to maximize the efficiency of the Trombe wall and minimize the dependency on active systems such as air conditioners, which

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results in creative designs and innovations that serve a variety of distinguishable environmental requirements. The conventional Trombe Wall is built using high heat-storage capacity materials such as concrete, and the external surface of the wall is coloured black to improve the absorption rate **[3],** a modification can be constructed in the wall to induce natural ventilation of $20 - 90\ m^3/h$ with a dark-coloured $2\ m^2$ wall and a $14\ cm$ air gap**[4]**. Another design is a zigzag Trombe wall, which aids in reducing the excessive heat gain and glare of sunny days **[3]**.

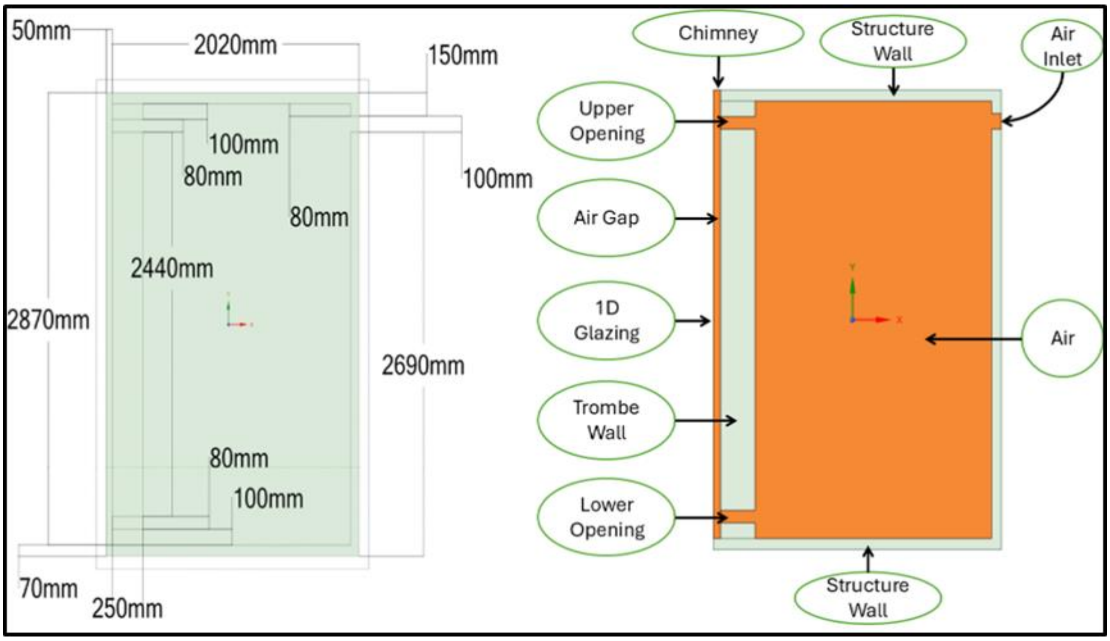

Figure 1. Structure

This paper will examine and analyze the performance of the conventional Trombe wall using different materials like concrete, cement and brick using computational fluid dynamics **(CFD)** by ANSYS Fluent in two dimensions **(2D),** specifically the air gap region. With the availability of high-speed computation and storage systems, the utilization of numerical simulation as an alternative method for problem-solving is earning prominence, demonstrating the potential to enormously reduce the necessity for physical experimental trials. This leads to valuable insights into the air dynamics and the temperature distributions inside the air gap, as well as the upper and lower openings **[5]**.

Structure Geometry

The assumed design for the simulation, as illustrated in Figure 1, portrays a structure measuring $(2940 \times 2070)\ mm$. It features a concrete wall with a thickness of $70\ mm$ encompassing all sides excluding the left side, which consists of common glass with a height of $2870\ mm$. The Trombe wall measuring dimensions are $(2800 \times 250)\ mm$,

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positioned $50\ mm$ away from the glass results in forming an air gap. Further, it features a $80\ mm$ upper opening and lower opening.

Meshing Process

In the process of CFD simulations, the meshing creation holds a crucial role. It is essential to approach this phase with tremendous care and consideration to acquire outcomes that accurately portray real-world conditions. In the present study, utilization of straightforward meshing procedures yielded satisfactory results. Specifically, a uniform element size of **10mm** was conducted to shroud the totality of the domain, while a finer meshing procedure with an element size of **5mm** was particularly applied to the air gap. The criteria for the chosen element size of the domain are in Table 1.

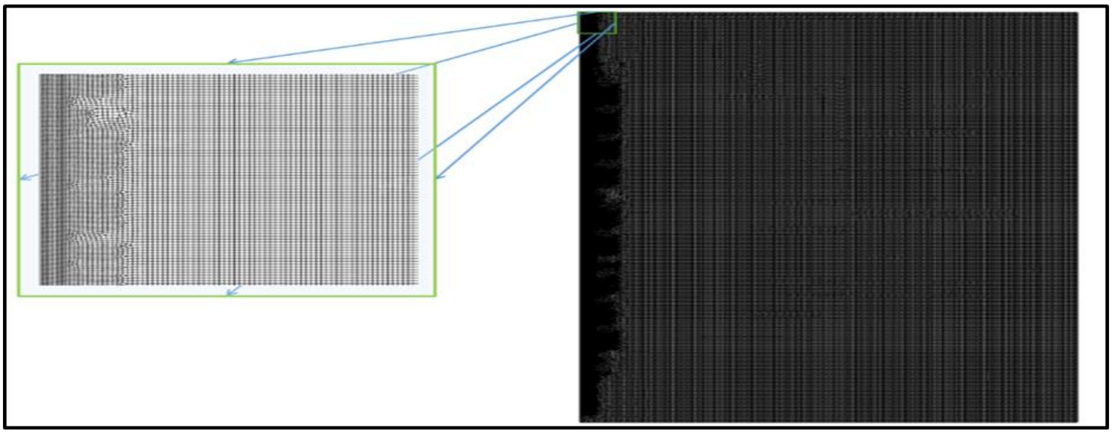

Figure 2. Meshing domain with illustration of small section of air gap

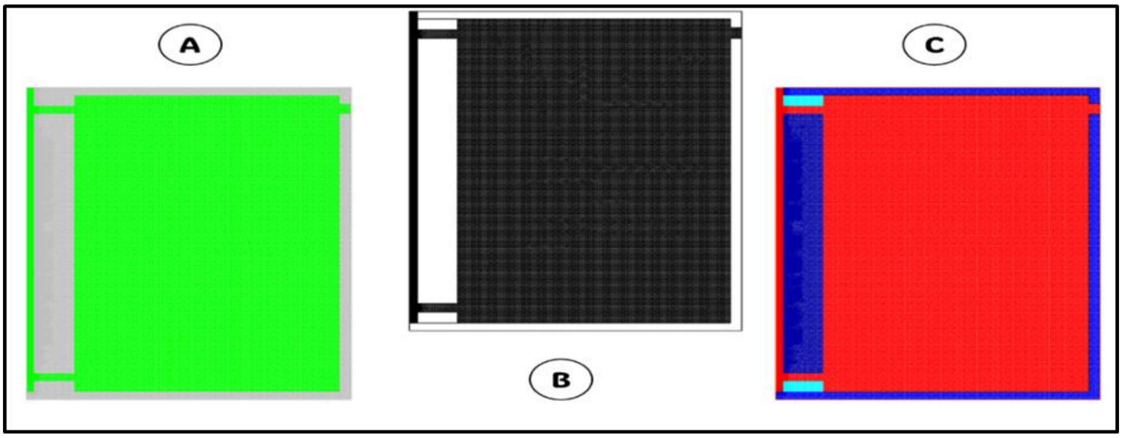

Figure 3. Mesh of the entire domain

The finer meshing in the air gap area permits a sufficiently detailed illustration of the flow dynamics within that specific area. The chosen element sizes are the results of trial simulations that were conducted for grid independent solution.

Simulation Parameters

The simulation configuration constitutes three characteristic phases subjected to identical conditions corresponding to the trial materials of concrete, cement and brick. The following properties in Table 2 are set according to the ANSYS fluent defaults.

Table 1. Meshing Criteria

Criteria	Min Value	Max Value	Average Value	Recommended Values
Skewness (S)	1.3057e-10	0.63469	1.1536e-2	S < 0.85
Aspect Ratio (AR)	1	2.4848	1.0436	1 < AR < 5
Orthogonal Quality (OQ)	0.63564	1	0.99865	OQ = 1
Element Quality (EQ)	0.36192	0.99971	0.98518	EQ = 1

Table 2. Material Properties

Material	Density kg/m^3	Specific Heat J/ (kg K)	Thermal Conductivity W/ (m K)
Air	incompressible ideal gas	1006.43	0.0242
Glass soda lime (common glass)	2464.9	898.61	1.0073
Concrete	2391.7	936.35	2.0712
Cement	1990	839.57	0.84853
Brick engineering	2291.3	798.44	0.89443

The Three phases of the simulation are subjected to identical boundary conditions. As portrayed in Figure 1, the structure wall is constructed from concrete with an internal emissivity of **0.85** and a diffuse fraction of **0.5**. A free stream temperature of **10°C** and a convective heat transfer coefficient of **10 W/ (m^2 K)** is applied externally as convective thermal boundary condition. The structure comprises of four openings - an Air Inlet and a Chimney, which are both sealed with glass windows and subjugated under the exact convective thermal boundary conditions of that of the structure wall. The Upper and Lower Openings are unsealed to facilitate air circulation within the interior of the structure and simulate the heating process in Winter season.

The glazing boundary is composed of soda-lime glass and is subjected to mixed boundary conditions of radiation and convection. The convection conditions align with those of the structure wall. Regarding radiation, it is characterized by an external radiation temperature of **30°C**, an external emissivity of **0.85**, and a diffuse fraction of **0.5**. Solar rays are induced parallel to the horizontal axis, penetrating the glass into the Trombe wall. The direct irradiation measures **1000W/m^2**, while the diffuse irradiation amounts to **200W/m^2**.

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The simulation encompasses Three phases of which the Trombe Wall is implicated, the first phase of the simulation undergoes with the Trombe Wall composed of concrete, tailed by the usage of cement in the second phase, and the third phase involves the implementation of brick.

The selected standard model for simulation is heat transfer, a laminar and discrete ordinate model with an initial domain temperature of **10°C**, also the simulation is executed in a transient first-order implicit mode with **5000**-time steps for **100** Iterations for every step with a time step size of **5s,** satisfying the criteria of Courant Number (**CFL Condition**) equal to **50** for maximum time step size with stable solution, keeping in mind the implicit solvers are more stable and can handle higher CFL numbers. The following solver settings are chosen according to trial simulations that conducted prior to the actual simulation, confirming the solution stability and convergence:

Table 3. Solver Settings

	Under-Relaxation Factors	Discretization Scheme
Pressure	**0.4**	**Second Order**
Density	**0.4**	/
Body Forces	**0.6**	/
Momentum	**0.4**	**Second Order Upwind**
Energy	**0.8**	**Second Order Upwind**
Discrete Ordinates	**0.8**	**First Order Upwind**

Mathematical Model

The Trombe Wall system can be simulated by solving numerically the following equations [6]:

Energy Equation:

$$\frac{\partial(\rho E)}{\partial t} + \nabla \cdot \left(\vec{V}(\rho E + p)\right) = \nabla \cdot \left(k\,\nabla T + \left(\bar{\bar{\tau}} \cdot \vec{V}\right)\right) + \dot{S}_g$$

Mass Conservation Equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \left(\rho \vec{V}\right) = S_m$$

Momentum Conservation Equations:

$$\frac{\partial(\rho \vec{V})}{\partial t} + \nabla \cdot \left(\rho \vec{V}\vec{V}\right) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho \vec{g} + \vec{F}$$

The DO Model Equations

$$\nabla \cdot \left(I_{(\vec{r},\vec{s})}\vec{s}\right) + (a + \sigma_s) I_{(\vec{r},\vec{s})} = a n^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_2}{4\pi} \int_0^{4\pi} I_{(\vec{r},\vec{s}')}\, \Phi(\vec{s} \cdot \vec{s}')\, d\Omega'$$

Results and Discussions

The simulation of three phases demonstrates by displaying a visual representation of contours as illustrated in figure 4 and figure 5. The contour of static pressure indicates a low static pressure in the middle of the air gap because of the rising of warm air due to decrease of its density, which is a consequence of the natural convection that happens near the wall, but as it gets nearer to both of upper and lower openings the pressure increases due to the present of cooler air near the openings, particularly at the lower opening due to the replacement of cooler air to the rising of warm air, also causing the air movement and circulation in the system. The contrast between the pressure distribution in the system by various materials can be observed clearly, the difference in pressure in the brick-made system (***BRS***) and the cement-made system (***CES***) is nearly equivalent, and larger than the difference of pressure in the concrete-made (***COS***) system indicating a faster airflow at the first two materials, which can be noticed in the velocity contour. The difference can be attributed to the unique specific heat value of each material, a lower specific heat value means a lower storage capacity of material to hold heat, causing the material to heat faster. The volumetric heat capacity of the simulated materials:

$$c_v = \rho c$$

Where c_v is the heat capacity of the material per unit volume ($J/(k\,m^3)$), ρ is the density, and c is the heat specific value. The volumetric heat capacity of cement is lowest at value of $1.67\ MJ/(k\,m^3)$, followed by brick at $1.83\ MJ/(k\,m^3)$, and finally the concrete having the largest heat capacity at value of $2.24\ MJ/(k\,m^3)$. These values explain the reason why **CES** has higher temperatures that reach $80°C$, as cement needs less heat energy to raise its temperature one unit.

For that reason, as the difference of pressure in the air gap of the Trombe Wall system depends solely on the temperature variation, it noted from the contours that cement has the largest temperature difference which corresponds to a larger pressure difference that leads to a higher mass flow rate and velocity of air, followed by brick, and then concrete. Figure 6 to Figure 10, portray the temperature distribution and velocity profile at the air gap in the horizontal direction. The temperature distribution for all systems exhibits similar behavior, near the wall ($x = 0.95$) has a higher temperature than the air near the glass ($x = 1$), excluding the regions nearby the openings, which indicate basically steady air temperature at the horizontal axis as the air moves in and out of the air gap in that temperature. For the velocity profile, the air that enters the air gap through the lower opening collides with the glass at velocity of $0.05 m/s$, at that instant the air from the air gap below the lower opening attempts to ascend with a faster velocity near the glass because of the entering of cool air suddenly, results in an increase of air velocity to nearly $0.125 m/s$ for all systems. As the air ascends, the velocity reduces near the glass due to convection that transpires outside of the glass which maintains its temperature at nearly $11°C$, On the other hand, the velocity close to the wall increases as the air ascends until it reaches the middle of air gap where the pressure at the lowest then it starts to decrease again due the increase of pressure as getting closer to the upper opening.

Furthermore, the velocity profile has two peaks, near the wall and near the glass, with a larger air velocity near the wall. The cause is the buoyancy effect that occurs near both of the wall and the glass, forming a boundary layers where the velocity gradients are steep. The air moves faster in these layers due to the temperature difference, while it moves slower in the core region of air gap due to the temperature gradient being less pronounced.

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Figure 11 illustrates the temperature distribution and velocity profile at the air gap also, but in the vertical direction along the air gap(*being* $\boldsymbol{y = 1.5}$ *is the highest point in the air gap and* $\boldsymbol{y = -1.47}$ *is lowest point in the air gap which is equivalent to air gap height* $\boldsymbol{2.87m}$), it notices that maximum velocity emerges near the wall at a distance from the wall, while at a distance $\boldsymbol{3cm}$ from the wall, the velocity is the lowest which indicates that most of the airflow arises at the sides near the wall and glass. The figure portrays also the variation of the temperature and velocity profile for each material, noting that cement has an overall higher air gap temperature and higher velocity, followed by brick and lastly concrete.

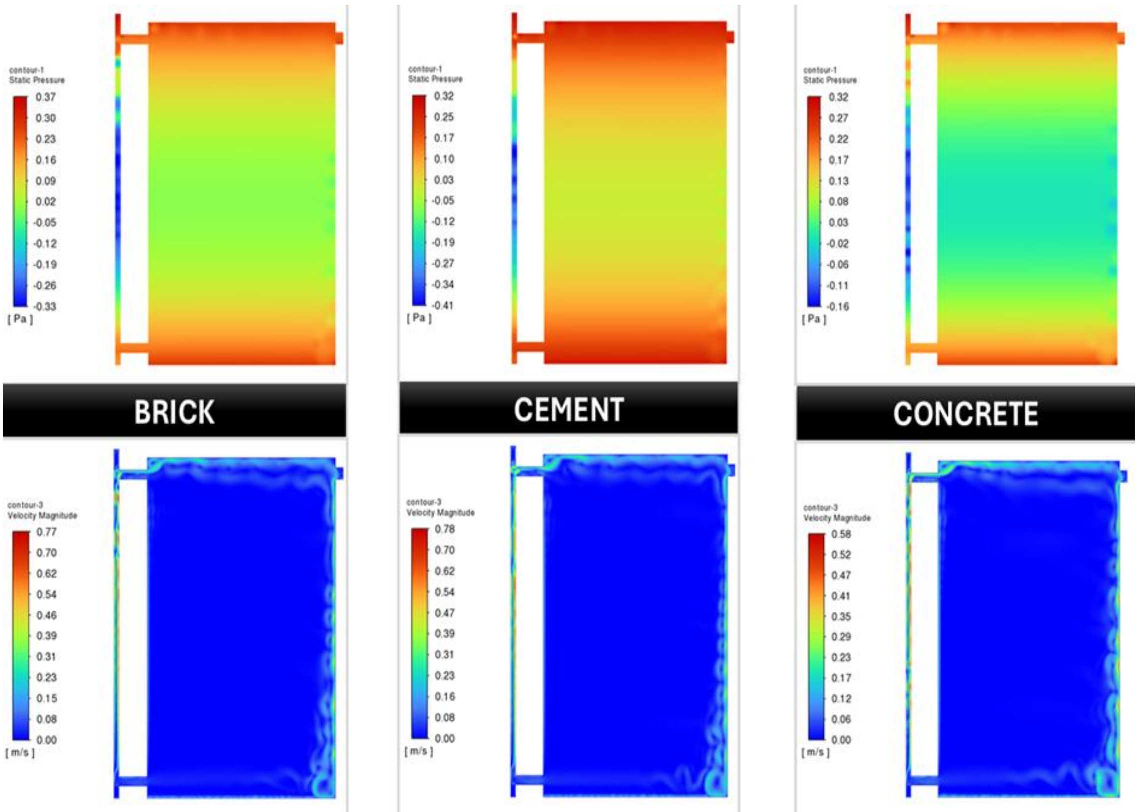

Figure 4. Contour the Pressure and Air Velocity

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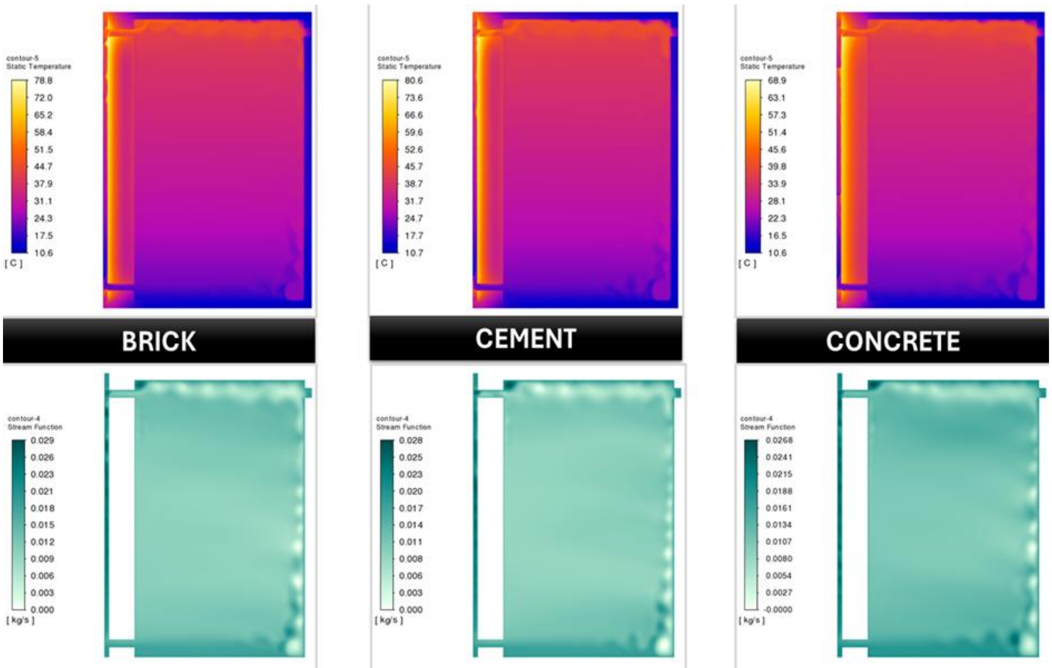

Figure 5. Contour the Temperature and Air Stream

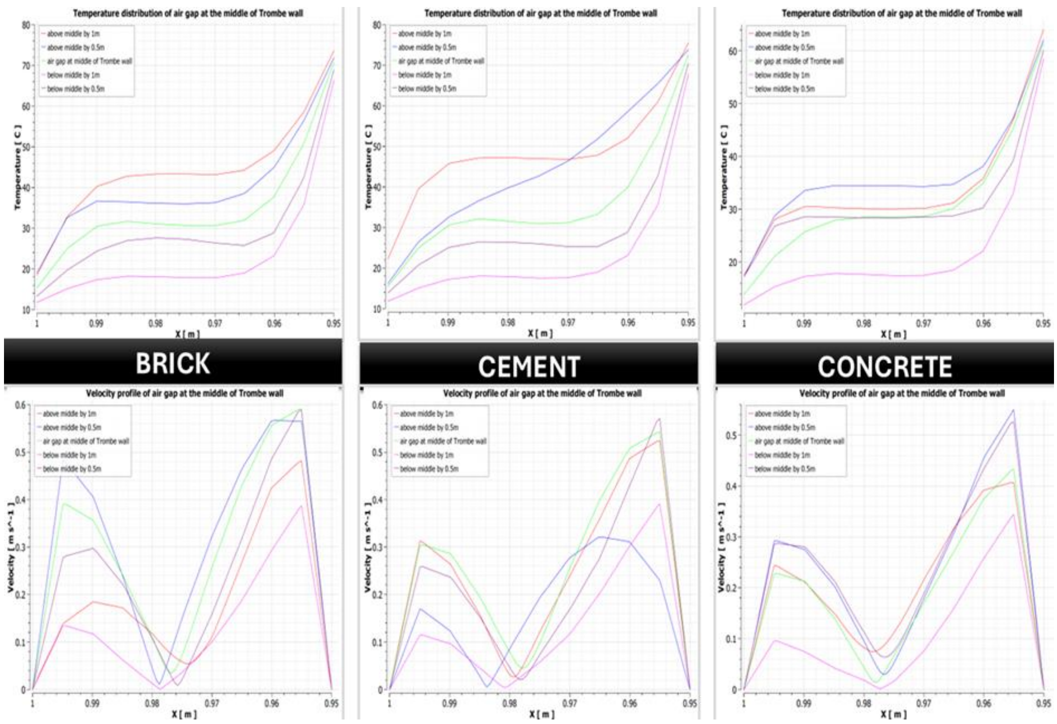

Figure 6. Temperature and Velocity at the Middle of Air Gap

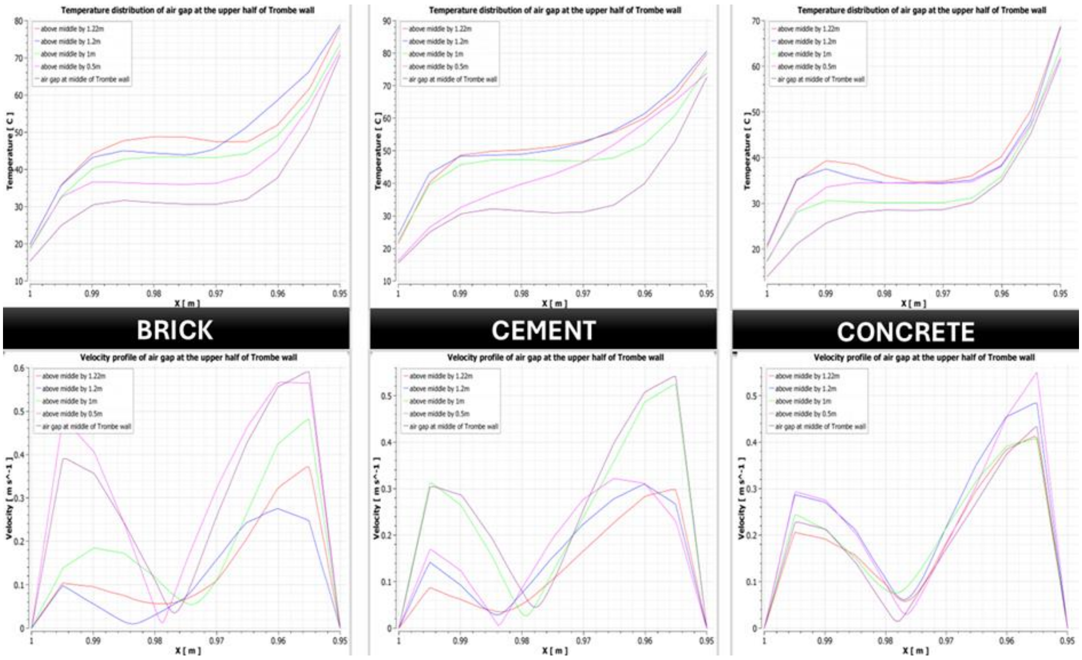

Figure 7. Temperature and Velocity at the Upper Half of Air Gap

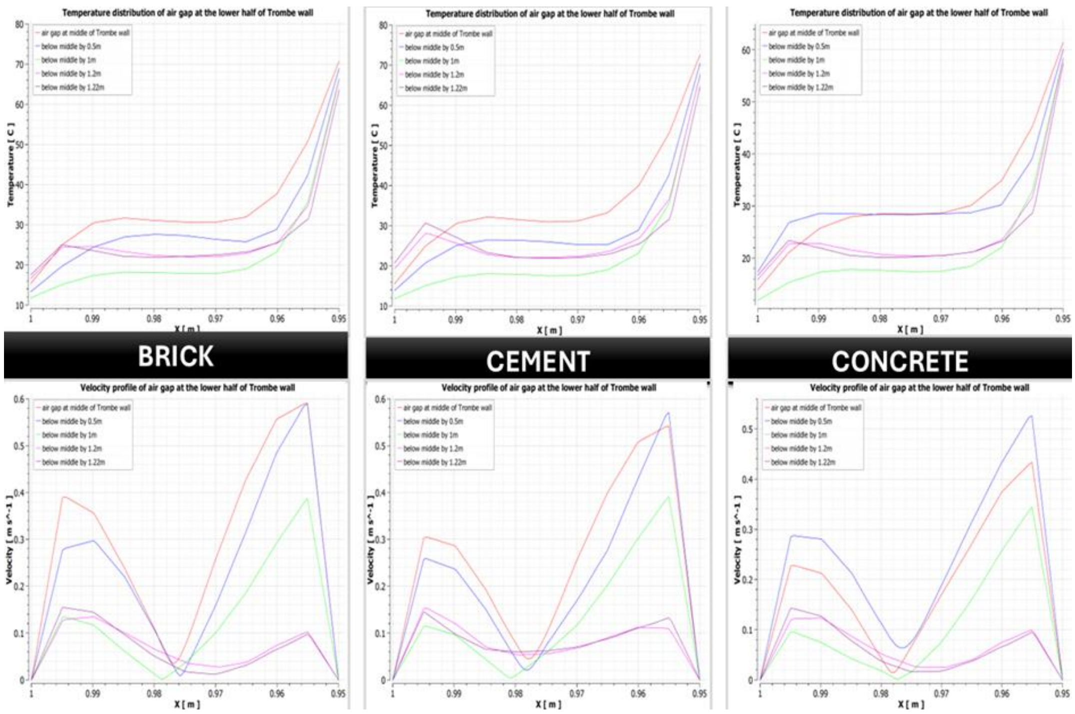

Figure 8. Temperature and Velocity at the Lower Half of Air Gap

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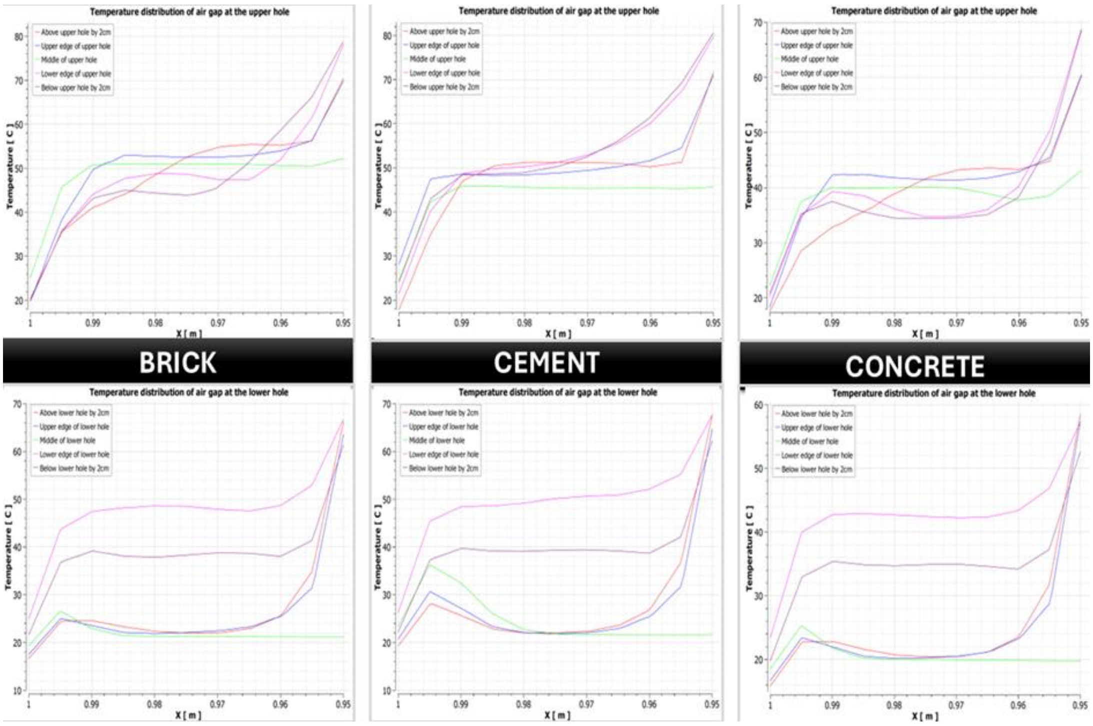

Figure 9. Temperature Distribution at Upper and Lower Openings

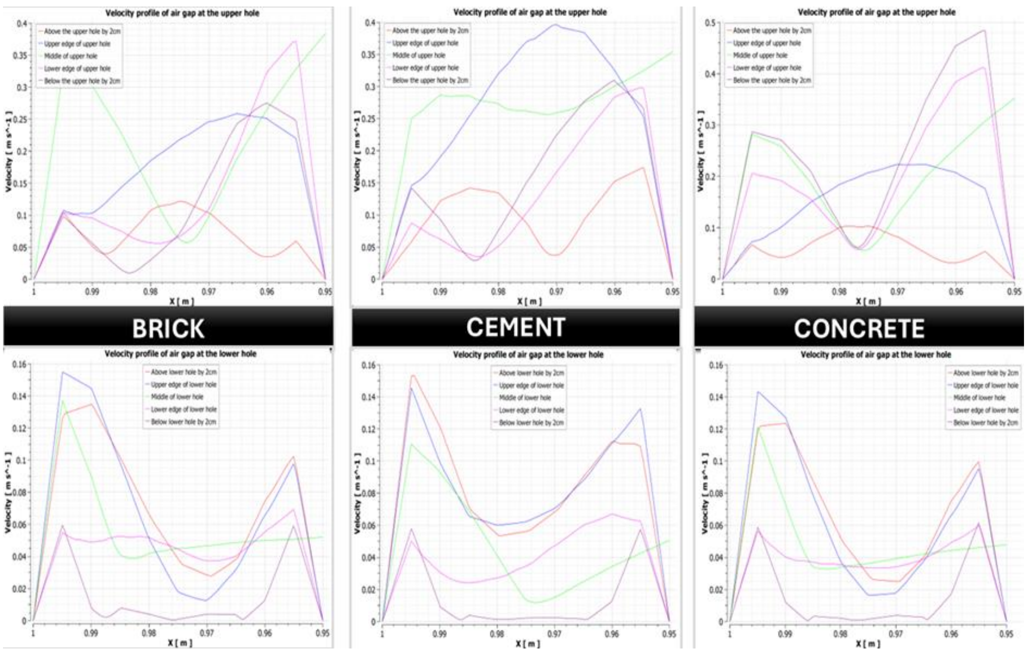

Figure 10. Velocity Profile at Upper and Lower Openings

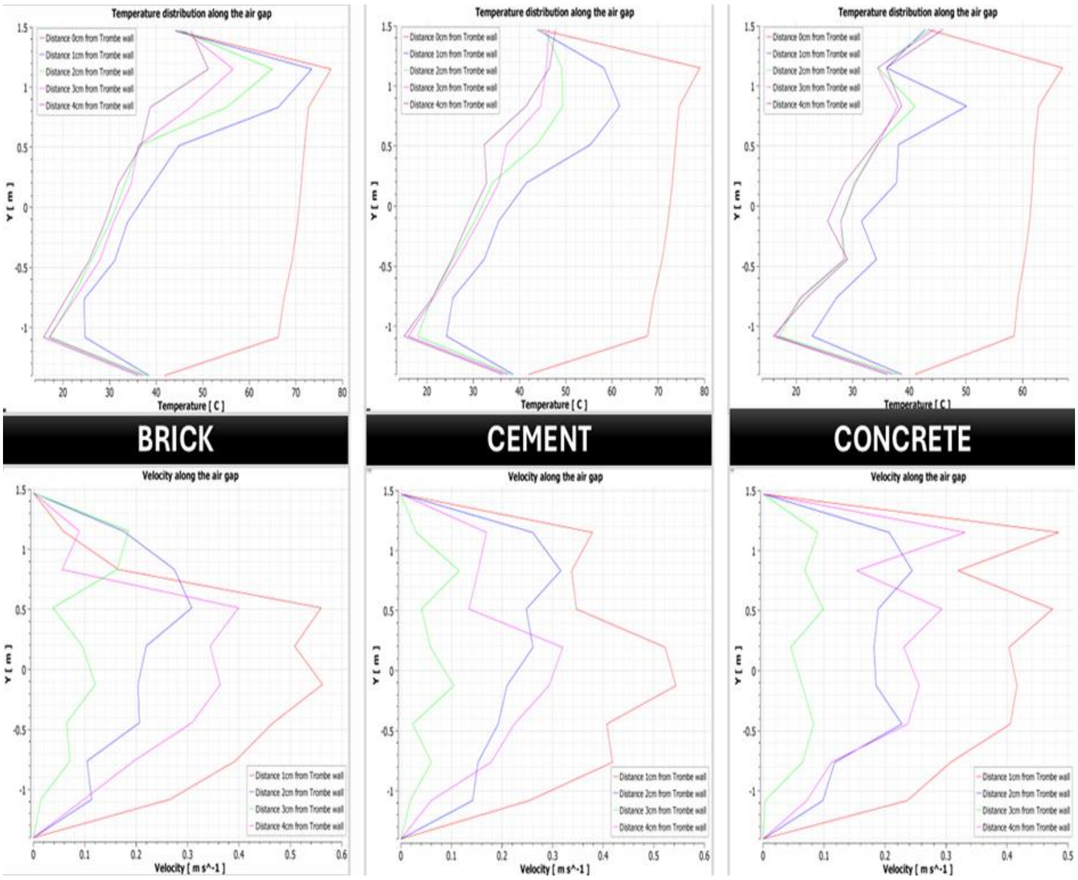

Figure 11. Temperature and Velocity along the Air gap

Additionally, the **COS** system has the highest efficiency of all with $\mathbf{74}\%$, then **BRS** system with $\mathbf{64.9}\%$ and finally **CES** system with $\mathbf{62.4}\%$. The main factor for the difference of efficiency between systems rises from the heat capacity of the material, the higher the total heat capacity of a given material that the system constructed from, the higher the efficiency of that system. The efficiency of the Trombe Wall system is calculated by dividing the useful heat energy gain over the solar incident energy.

Figure 12 shows the temperature in the middle of the room at height of $\mathbf{1.47m}$ with time period of almost **7** $\boldsymbol{hours}$**,** being the **CES** has the highest temperature, followed by the **BRS** and lastly by considerable margin the **COS**.

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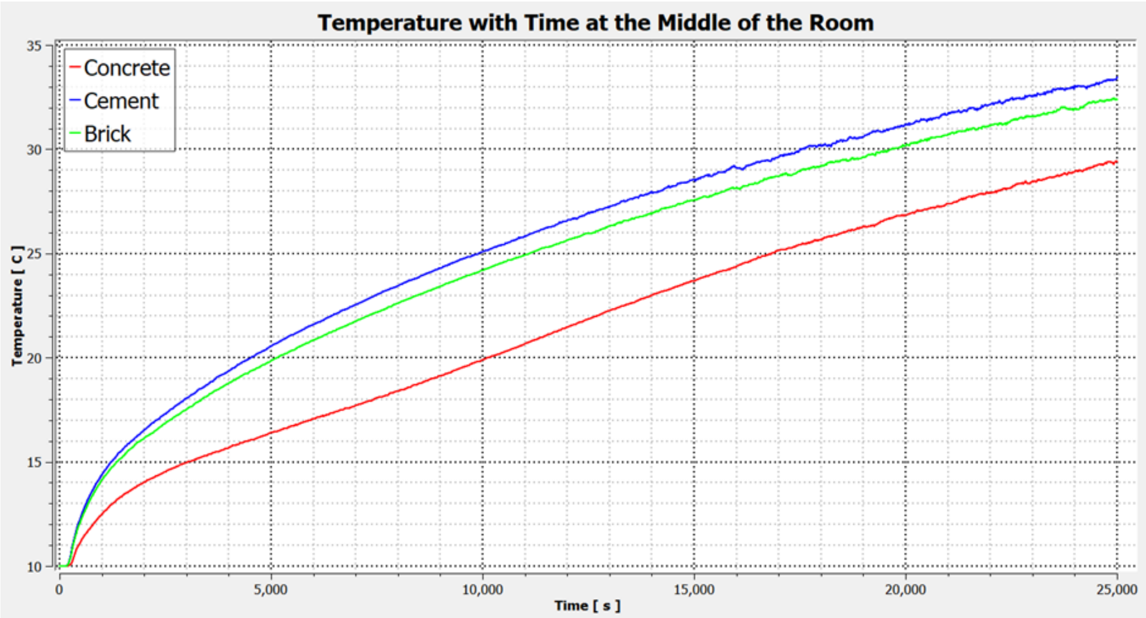

Figure 12. Temperature vs Time

Conclusion

The study finalized that both **CES** and **BRS** can warm the room faster than **COS**, also it can induce a higher air flow rate, but it needs to regard the excessive heat in the structure in design, so it maintains comfortable temperatures. In the other hand, the **COS** has the highest efficiency of the simulated systems, results in having more capability to store heat for longer time more than the others, which fits the conditions of heating system at winter seasons. It concludes that, a Trombe Wall made from higher total heat capacity tends to have a higher efficiency, but it features an air gap with less temperature and air flow rate. For that, a Trombe Wall built from a lower heat capacity material, features an air gap of a higher temperature, a higher air flow rate and less efficiency, which fits the conditions of cooling systems at summer seasons. The CFD simulation by Ansys can provide an essential understanding of air temperature and velocity distributions inside the structure. It was observed from the simulations that constructing the Trombe wall from various materials could influence the temperature distribution inside the structure.

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