CFD EVALUATION OF THE POTTERY WATER WALL IN A HOT ARID CLIMATE OF LUXOR, EGYPT

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ABSTRACT

This paper aims to evaluate the Pottery Water Wall in a hot arid climate using CFD simulation. The Pottery Water Wall is a passive system and an upgrade to the Water Wall. The Pottery Water Wall is a combination of a Water Wall and Porous Ceramic Pipes for evaporative cooling. First, the study will evaluate the efficiency of the Pottery Water Wall in cooling and heating in the most extreme climatic conditions of winter and summer in Luxor, Egypt. This study will aid determining the ability of the Pottery Water Wall to cool and heat buildings and its ability to achieve thermal comfort. The study found that the Pottery Water Wall's cooling ability ranges between 4ºC to 10ºC, while its heating ability ranges between 4ºC to 15ºC. The Pottery Water Wall achieved thermal comfort for 62.5% of a day resembling extreme summer and achieved thermal comfort 62.5% of a day resembling extreme winter. In conclusion, the Pottery Water Wall can reduce cooling and heating demand by 88% at the extreme climatic conditions of Luxor, Egypt.

KEYWORDS

Passive design, pottery water wall, water wall, porous ceramic, evaporative cooling, CFD

1. INTRODUCTION

In the past few decades, passive solar design has been developed and harnessed as a response to the energy crisis and air pollution and global warming. Building energy use accounts for at least 20 to 40% of all energy usage. Most of the energy that is consumed by buildings is used for heating and cooling [1]. One of these passive design systems is the thermal storage wall (solar wall), which is a passive solar system mainly used for the heating and cooling of buildings. The thermal storage wall is a medium for thermal storage placed between the glazing and the living quarters. The thermal storage medium stores heat from the Sun and then redistributes it throughout the day and night for heating. The thermal storage wall manipulates indoor temperature, without affecting humidity or inducing ventilation because it uses only radiant heat transfer [2, 4]. The main issue affecting thermal comfort in hot arid climates is humidity due to dryness.

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Regions with a hot arid climate such as Luxor, Egypt, suffer from excessive heat and dryness. Therefore, the means to achieve thermal comfort in such climates are cooling and humidification. A traditional solution to achieve thermal comfort in hot arid climates is by using a phenomenon called evaporative cooling. Evaporative cooling is the evaporation of water if air with a lower dew point passes by, causing the decrease of the temperature of the air and the increase of its water content (humidity). The practical use of this phenomenon dates back to ancient Egypt, where porous clay vessels filled with water were put in a wind catcher to cool and humidify air due to the porosity of the clay vessel [1], as shown in the drawings in the Tomb of Neb Amun in Thebes (Modern Day Luxor) [6]. However, modern evaporative cooling was not commercialized and used until the 1920's of the last century in desert coolers, which is a cooling device that uses evaporative cooling to cool air [5].

This paper aims to introduce a system that combines both the large heat capacity of thermal storage walls and the high cooling and humidification capacity of evaporative cooling. The Pottery Water Wall is a combination between the water wall (thermal storage wall using water) and porous ceramic for evaporative cooling. The Pottery Water Wall is patented to the first author in the Egyptian Patent Office under request No. 2010040663. This paper evaluates the Pottery Water Wall's efficiency in a hot arid climate using CFD simulation, specifically using the program ANSYS FLUENT. *"CFD (Computational Fluid Dynamics) is a branch of fluid dynamics and had its inception from the 1930's with the development of computer simulation technique. It combined with fluid dynamics, numerical method and computer graphics as integrity. It is a powerful calculation and simulation technique which can be used to analyze the properties of fluids."* [11]. FLUENT was validated by [12] M. B. Gadi (2000) who compared the results of two simulations conducted on a water heater used for the passive heating and cooling of a building in North Africa. M. B. Gadi (2000) found that FLUENT gave results similar to the results of the experiment and thereby validated the accuracy of FLUENT. FLUENT was further used in many other studies and vetted for accuracy [13,14].

2. THE POTTERY WATER WALL

The pottery water wall is a passive system used for cooling, heating, and humidification. It is a combination between the water wall and an evaporative cooling system that uses porous ceramic. It harnesses the advantages of both systems to increase their efficiency and overcome their disadvantages. The addition of evaporative cooling to the water wall increases its heat transfer capacity and adds ventilation and humidification. The pottery water wall consists of an ordinary water wall containing an opening through the container to the outdoors with porous ceramic piping to add evaporative cooling as shown in Figures 1 and 2. The water drum acts as a thermal storage medium and radiates heat into the room or building while the porous pottery piping evaporates water from its surface to the air passing through the opening induced by cross ventilation or wind power. The air resulting from this process is more humid and cooler or warmer according to the need. The air passing through the Pottery Water Wall ventilates the room. The system is most effective in hot and arid climates where humidity is always low, and there are huge swings in temperatures throughout the day, because the use of evaporative cooling is most effective in dry climates.

FIGURE 1. Diagram of the Pottery Water Wall.

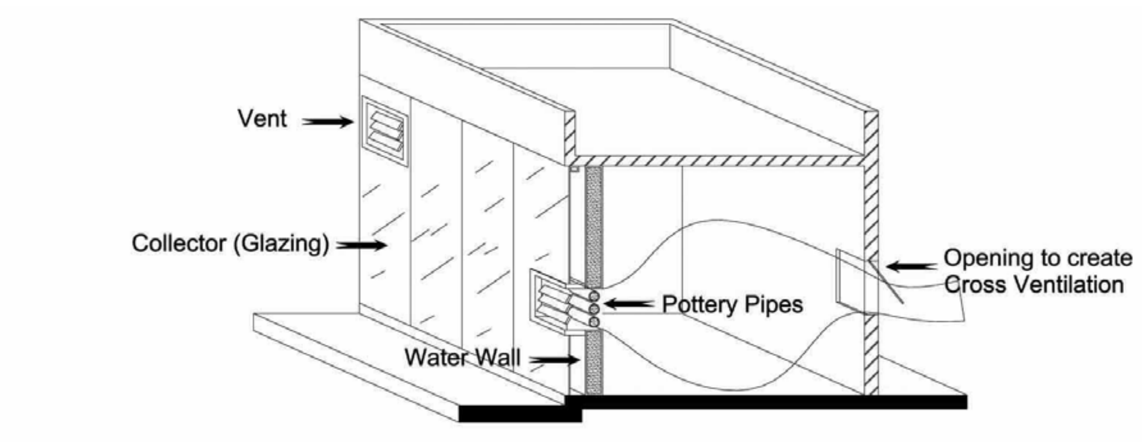
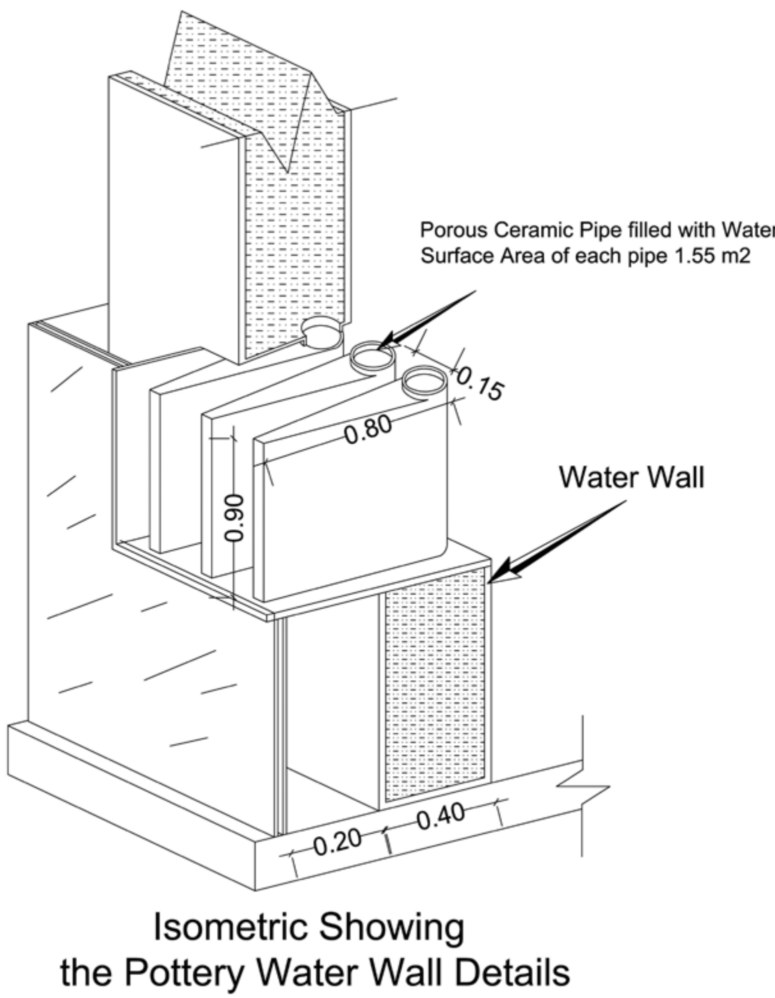


FIGURE 2. Isometric showing the Pottery Water Wall components and Pipe fixing in the wall.



3. SIMULATION BUILDUP AND PROCEDURE

The study is divided into two simulations. Simulation 1 compares different designs of the Pottery Water Wall in ultimate climatic conditions to define the most efficient design. Simulation 2 simulates the Pottery Water Wall approximating two days resembling extreme cold weather and extreme hot weather. The results are then compared with the ASHRAE thermal comfort criterion [17] to define the Pottery Water Wall's ability to achieve thermal comfort. The simulations are discussed more extensively in the next sections.

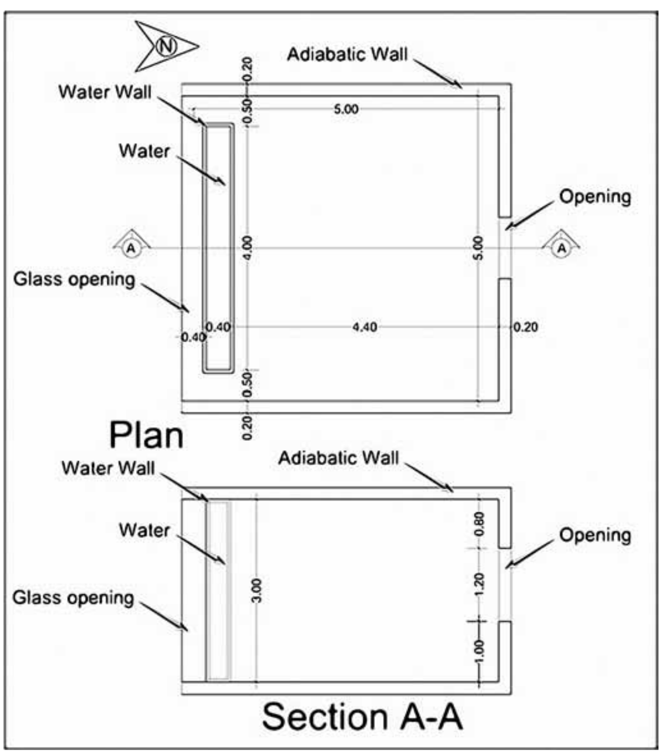
3.1 Software and Equipment

The software used for modeling is ANSYS Workbench, and then the models were meshed by ANSYS Meshing using moderate meshing size. ANSYS Fluent was used for the simulation using the Laminar Flow Energy Equation and Radiation (Rosseland) from the simulation modules to simulate heat transfer. Laminar flow is used to neglect the heat transfer caused by turbulence and focus on the heat generated from the direct contact between air and the porous ceramic only.

3.2 Base Models

The base model for the study is an adiabatic room with walls 20 cm thick. The room's inner dimensions are 5 L X 5 W X 3 H meter as shown in Figure 3. The total inner volume is 75 m^2, which is the volume of a typical room in a typical traditional house in Luxor. Behind the south Façade, a steel container filled with water (Water Wall) is placed 20 cm from the south façade. The water container is 4.00L X 0.40W X 3H meter with a total volume of 4.8 m3, while the steel is 4 mm thick.

FIGURE 3. Base model for simulation.

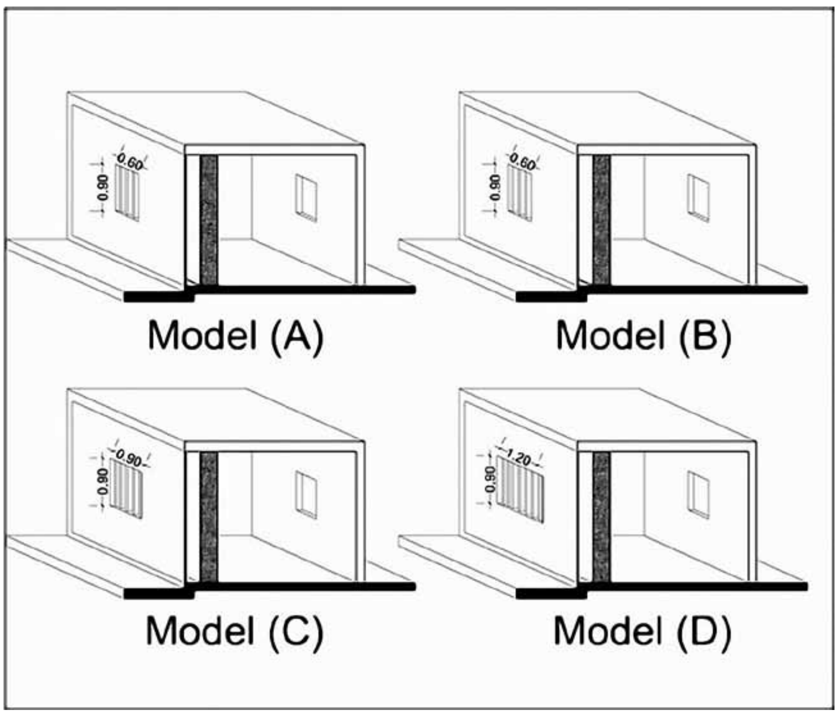


The porous ceramic pipe has a surface area of 1.55 m^2 for each pipe, as shown in Figure 2. The pipes are shaped as an extruded triangle with a circular base. The circular base has a diameter of 15 cm wide, the height of the triangle from the circle's quadrant to the end is 80 cm, and the total height is 90 cm. The pipe is connected to the water container to circulate water between the pipe and container. The pipe is made up from high porosity porous ceramic 5 mm thick to enhance heat transfer.

3.3 Four Simulation Models

The four different models of the Pottery Water Wall in the study are named A, B, C, and D as shown in Figure 4. Models A and B have an opening of 90 X 60 cm with 3 porous ceramic pipes, but Model A's pipes are adiabatic to act as a comparison base to the other models since Model A resembles an inactive Pottery Water Wall. However, Model B's pipes perform in the heat transfer. Model C has an opening 90 X 90 cm with 5 pipes, and Model D has an opening 120 X 90 cm and 7 pipes that are performing heat transfer.

FIGURE 4. The four simulation models.



3.4 Heat Transfer Performance (Heat Flux)

The Water Wall's heat flux is deducted by [16] and ranged from 40 W/m^2 to 100 W/m^2 with an average of 50 W/m^2. Since the study uses a similar Water Wall and uses average water temperatures, the heat flux of the water wall in the study is 50 W/m^2.

By comparison, the porous ceramic pipes performance was calculated in a technical report by [8]. The technical report conducted several tests deducting that the 5mm thick high porosity ceramic has a heat transfer flux ranging from 50W/m^2 to 200 W/m^2 for both latent and sensible heat transfer. Therefore, the study uses 5 mm thick high porosity ceramic with a heat transfer coefficient of 100 W/m^2.

The temperature of the water in the system is based upon the performance of the water wall, and it changes according to the solar radiation and temperature variation from day to night. The range of temperatures used for the water in the cooling session is 15°C, 17.5°C, 20°C, 22.5°C ,and up to 25°C, resembling an average performance of a Water Wall in Luxor in summer derived from studies conducted by [3]. During the heating session, the water temperature ranges from 40°C, 37.5°C, 35°C, 32.5°C, and down to 30°C, resembling an average performance of a Water Wall in Luxor in summer derived from studies conducted by [3].

3.5 Program Set up

The Program setup is summarized in Table 1.

TABLE 1. Summary of The Program Set-up.

Variable		Value
Solver type		pressure based
velocity formulation		absolute
Air Flow Pattern		laminar flow
Heat Transfer Method		energy equation
Radiation Method		Rosseland radiation
Solution Method		SIMPLE
Gradient		Green-Gauss Cell Based
Momentum		Second Order Upwind
Energy		Second Order Upwind
Materials		**Value**
Air	density	1.225 Kg/m^3
	specific heat	1006.43 J/Kg-K
	heat conductivity	0.0242 W/m-K
	viscosity	1.7894 X 10^5 Kg/m-s.
Water	density	1000 Kg/m^3
	specific heat	4000 J/Kg-K
Heat Flux		**Value**
Water Wall		50 W/m^2
Porous Ceramic Pipes		100 W/m^2
Wind		**Value**
South wind		1 m/s

3.6 Simulation Procedure and Sampling Methodology

All the previous variables and procedures contributed in the simulation and led to the formulation of the methodology of the simulation. The simulation methodology and procedure are concluded as follows in the two simulations.

• 3.6.1 Simulation 1

Simulation (1) aims to compare four different designs of the Water Wall. The test is conducted at the ultimate temperatures of the year in Luxor, Egypt, which are 40°C for extreme summer and 3°C for extreme winter.

The simulation will be conducted on each model 10 times, five for cooling at the ultimate temperature of 40°C and for heating at the least temperature of 3°C. During the cooling session, air inlet temperature is set to 40°C and air velocity at the fixed value of 1 m/s. The water temperatures in the Water Wall and pottery pipe vary and are 15, 17.5, 20, 22.5, and 25°C as shown in Table 3.By contrast, the heating session inlet temperature is set to 3°C, inlet air speed is set to 1 m/s, and the water temperatures are 30, 32.5, 35, 37.5, and 40°C as shown in Table 2.

• 3.6.2 Simulation 2

Simulation 2 will simulate the most efficient model deducted from simulation 1 for 2 whole days; the 21st of June resembling extreme summer and 21st of January resembling extreme winter. The simulation will use the most efficient water temperature according to the results from simulation 1. Results will be taken every hour during the 24 hours of the two days using the temperature deducted from the meteorological data, giving 24 readings of indoor temperature on each day. The resulting data will show the thermal performance of the Pottery Water Wall for the whole period during the two days resembling the extreme weather conditions in Luxor, Egypt.

4. RESULTS AND ANALYSIS

4.1 Simulation 1 Results

After conducting the 40 simulations on the four models using different water temperatures for cooling and heating at extreme temperatures, Figure 5 shows the air flow paths through the 4 models during the simulation. Figure 6 shows some of the simulations during sessions C1, C2, H1 and H2.

FIGURE 5. Simulation 1, air flow diagram.

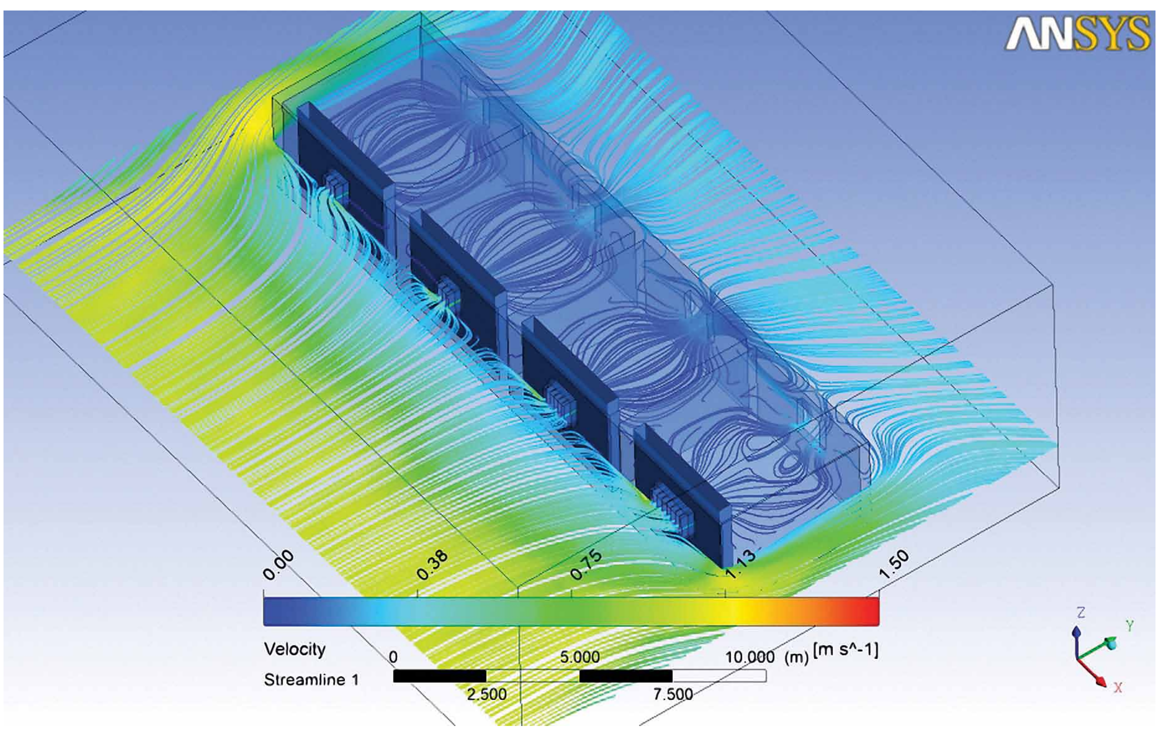
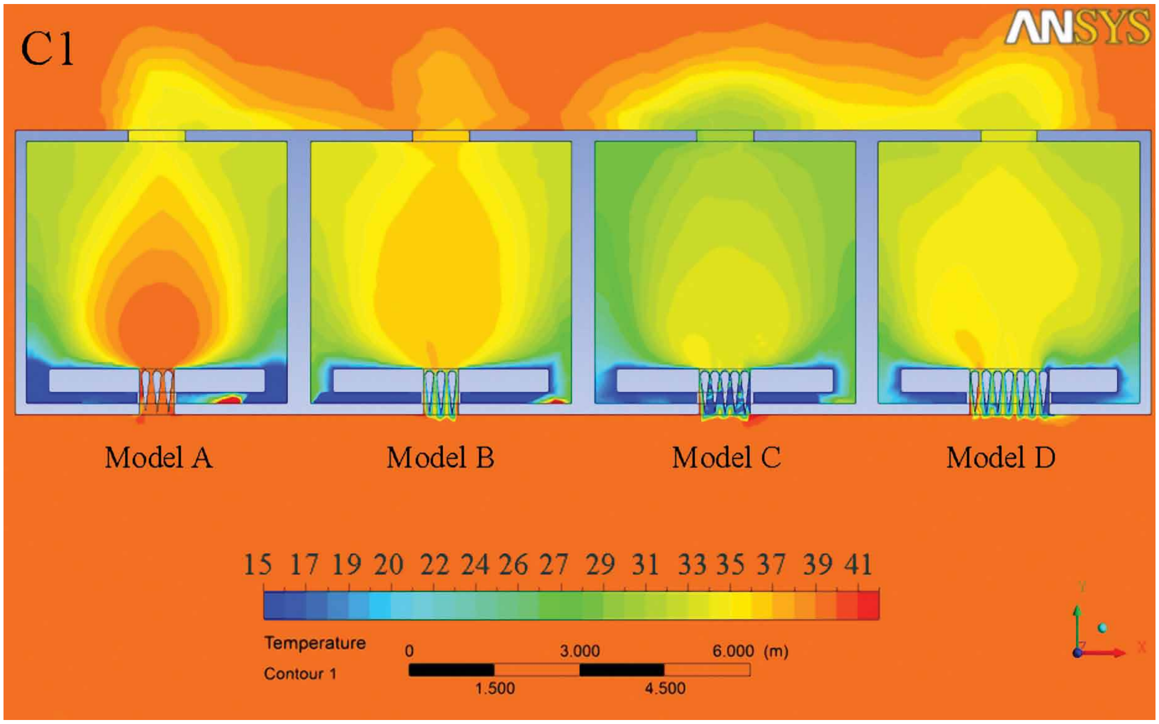


FIGURE 6. Simulation during session C1 only – not C1, C2, H1 and H2.



The results conducted from the 40 simulations are summarized and assembled in Table 2.

TABLE 2. Simulation 1 results table.

Model Name Opening & Surface Area (A-D)	Outdoor Temp. (H,C)	Water Temp. (1-5) °C	Name	Porous Ceramic Output temp.	Output temp. divergence	Room average temp.	Room average temp divergence
Model A 60 X 90 cm opening	40°C Cooling (C)	15	A-C1	40	0	36	4
		17.5	A-C2	40	0	37	3
		20	A-C3	40	0	37	3
		22.5	A-C4	40	0	38	2
		25	A-C5	40	0	39	1
	3°C Heating (H)	30	A-H1	3	0	5.5	2.5
		32.5	A-H2	3	0	6	3
		35	A-H3	3	0	6	3
		37.5	A-H4	3	0	6	3
		40	A-H5	3	0	7	4
Model B 60 X 90 cm opening 3 Pipes Porous Ceramic surface area 4.65 m²	40°C Cooling (C)	15	B-C1	35	4	33	7
		17.5	B-C2	36	4	34	6
		20	B-C3	37	3	35	5
		22.5	B-C4	38	2	36	4
		25	B-C5	38	2	36	4
	3°C Heating (H)	30	B-H1	6	3	7	4
		32.5	B-H2	6	3	7	4
		35	B-H3	7	4	8	5
		37.5	B-H4	9	6	11	8
		40	B-H5	10	7	12	9

TABLE 2. Simulation 1 results table continued.

Model C 90 X 90 cm opening 5 Pipes	40°C Cooling (C)	15	C-C1	33	7	29	11
		17.5	C-C2	34	6	30	10
		20	C-C3	34	6	30	10
		22.5	C-C4	35	5	32	8
Porous Ceramic surface area 7.75 m²		25	C-C5	35	5	33	7
	3°C Heating (H)	30	C-H1	9	6	12	9
		32.5	C-H2	9	6	13	10
		35	C-H3	12	9	16	13
		37.5	C-H4	13	10	17	14
		40	C-H5	14	11	18	15
Model D 120 X 90 cm opening 7 Pipes Porous Ceramic surface area 10.85 m²	40°C Cooling (C)	15	D-C1	34	6	31	9
		17.5	D-C2	34	6	31	9
		20	D-C3	36	4	33	7
		22.5	D-C4	38	2	36	4
		25	D-C5	38	2	36	4
	3°C Heating (H)	30	D-H1	7	4	10	7
		32.5	D-H2	8	5	11	8
		35	D-H3	9	6	13	10
		37.5	D-H4	9	6	13	10
		40	D-H5	10	7	14	11

4.2 Simulation 1 results analysis.

FIGURE 7. Simulation 1, cooling session and room's average temperature under different water temperatures.

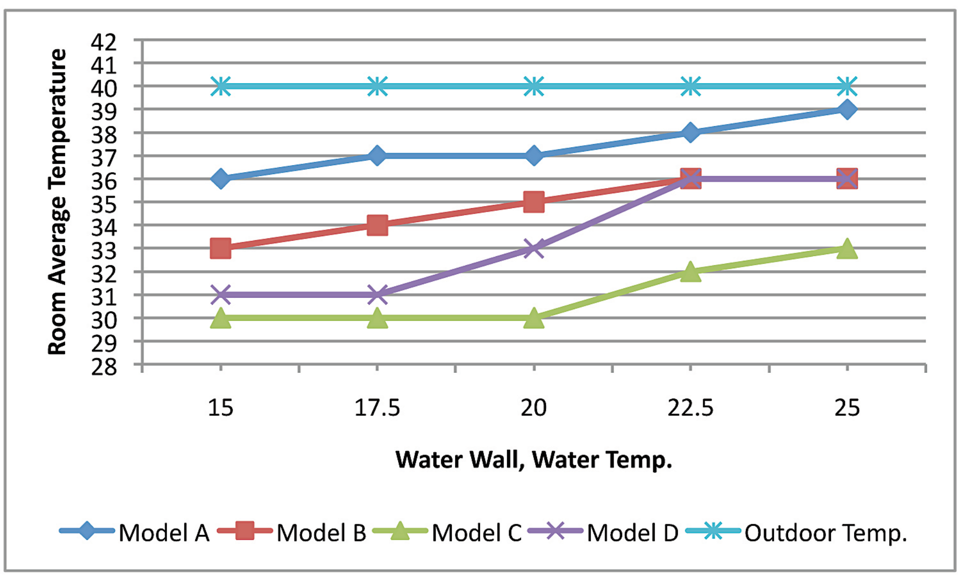


Figure 7 compares the effects of the four models on the indoor average temperature during the cooling session of simulation 1. The figure shows that Model C performed the best in cooling under all of the different water temperatures—its cooling ability ranged from 7°C to 10°C. While the Pottery Water Wall's cooling efficiency ranged from 4°C to 10°C.

FIGURE 8. Simulation 1, Heating session and room's average temperature for different water temperatures.

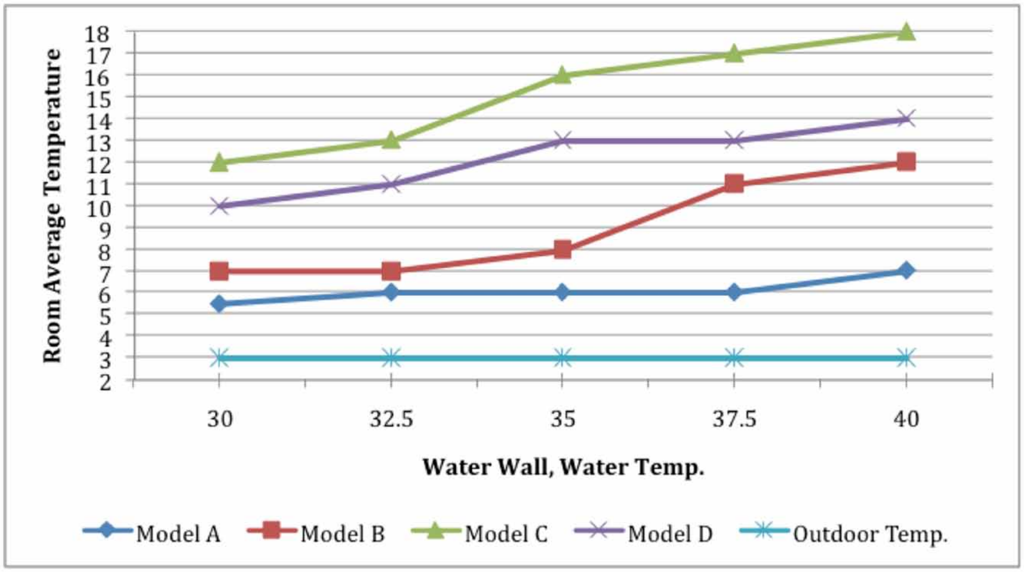


Figure 8 shows the resulting room temperature in simulation 1 during the heating session at an outdoor temperature of 3ºC. Model C performed the best in heating under all of the different water temperatures—its heating ability ranged from 9ºC to 15ºC , while the total range of heating was from 4ºC to 15ºC.

4.3 Simulation 1 Conclusions

• *4.3.1 Pottery Water Wall efficiency in cooling*

The Pottery Water Wall can cool a room under the worst criteria possible in Luxor, Egypt, from 4 to 10ºC. Model C which has a 90 X 90 cm opening and 5 porous ceramic pipes with a surface area of 7.75m^2 is the most efficient design of the Pottery Water Wall in cooling with a cooling ability ranging from 7 to 10ºC.

• *4.3.2 Pottery Water Wall efficiency in Heating*

The Pottery Water Wall can heat buildings under the worst criteria possible in Luxor, Egypt, from 4 to 15ºC. Model C which has a 90 X 90 cm opening and 5 porous ceramic pipes with surface area of 7.75m^2 is the most efficient design of the Pottery Water Wall in heating with a heating ability ranging from 9 to 15ºC.

• *4.3.3 The reason why Model C is the most efficient.*

Model C achieved the best results for cooling and in heating, regardless that Model D has a larger opening and more porous ceramic surface area to act in evaporative cooling. It was found that increasing the opening area reduced the amount of water in the Water Wall, decreased the heat capacity, and reduced the surface area of the water drum that acts in heat transfer with the room via radiation. Therefore, to achieve maximum efficiency, a balance between evaporative cooling from the porous ceramic pipes and the radiation of the water drum should be achieved. This case was achieved in Model C; therefore, Model C was the most efficient model in cooling and heating.

4.4 Simulation 2 Results

Simulation 2 was conducted on Model C for 24 hours on the 21st of June (extreme summer) and 21st of January (extreme winter) and readings were taken every hour. Figure 9 shows some of the simulations on the 21st of June at 3PM to 5PM. Figure 10 shows some of the simulations on the 21st of January at 6AM to 8AM.

FIGURE 9. Simulation 2, Simulation on the 21st of June from 3PM to 5PM.

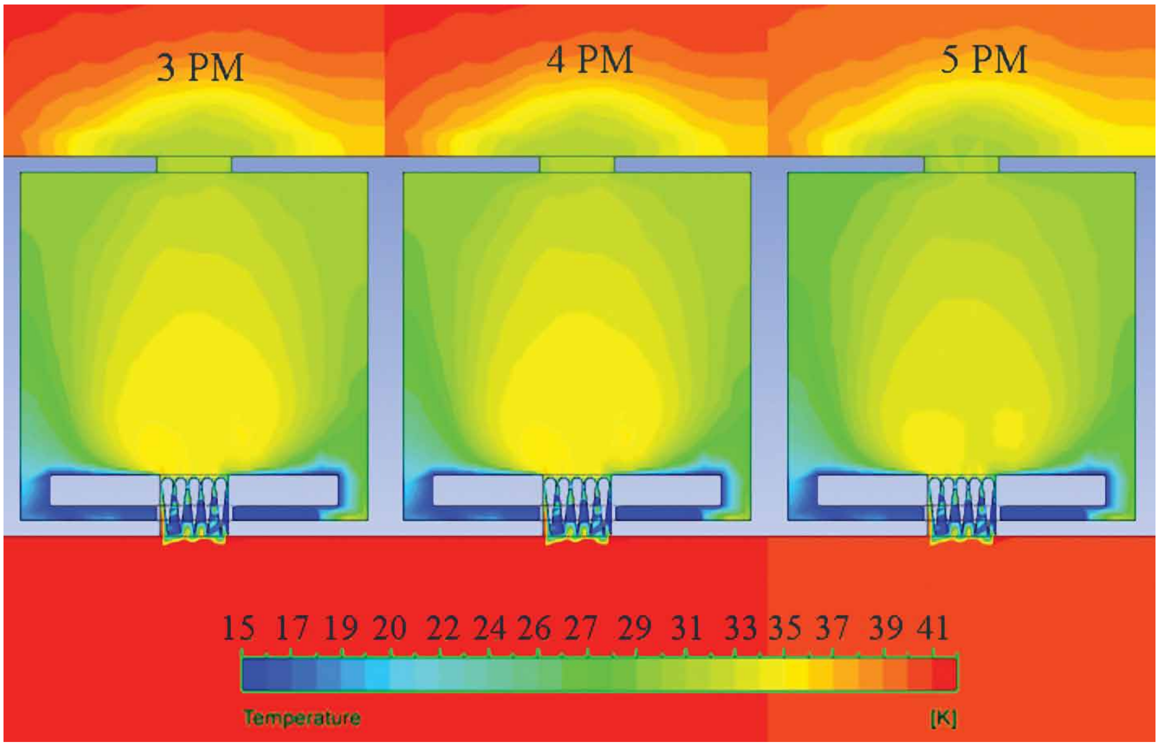
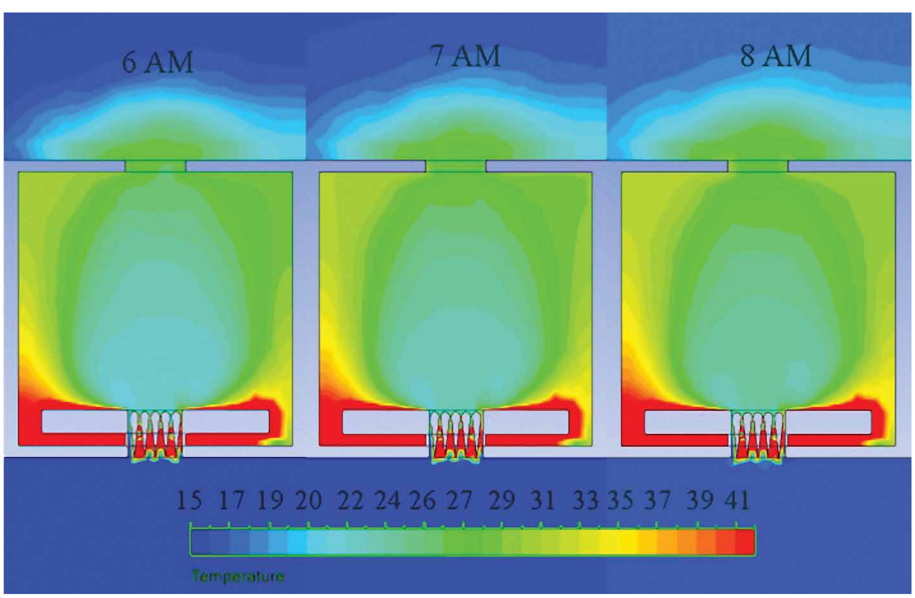


FIGURE 10. Simulation 2, Simulation on the 21st of January from 6AM to 8AM.



The results from simulation 2 are summarized in Table 3.

TABLE 3. Simulation 2 results.

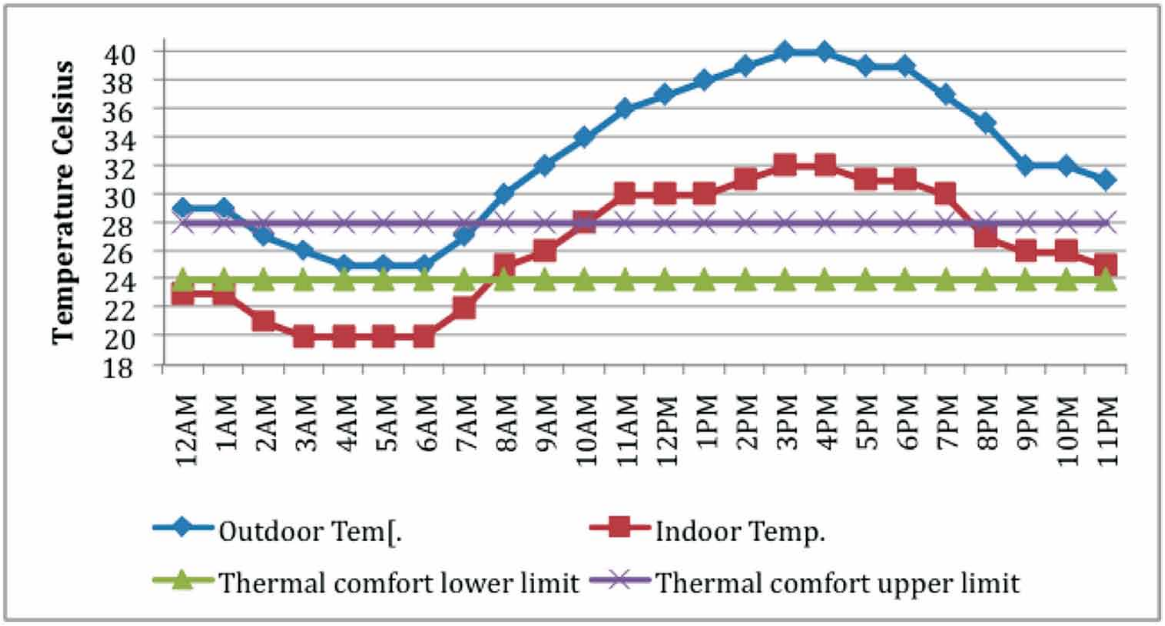
Cooling Session 21st of June simulation				Heating Session 21st of January simulation			
Model	Hour	Outdoor Temp. (°C)	Resulting aver. Temp. (°C)	Model	Hour	Outdoor Temp. (°C)	Resulting aver. Temp. (°C)
Most efficient Model C Most Efficient Water Temperature 15 C°	12AM	29	23	Most efficient Model C Most Efficient Water Temperature 40 C°	12AM	8	19
	1 AM	29	23		1 AM	7	17
	2 AM	27	21		2 AM	7	17
	3 AM	26	20		3 AM	6	15
	4 AM	25	20		4 AM	5	14
	5 AM	25	20		5 AM	5	14
	6 AM	25	20		6 AM	3	12
	7 AM	27	22		7 AM	4	13
	8 AM	30	25		8 AM	5	14
	9 AM	32	26		9 AM	10	20
	10AM	34	28		10AM	13	21
	11AM	36	30		11AM	15	22
	12PM	37	30		12PM	16	23
	1 PM	38	30		1 PM	17	24
	2 PM	39	31		2 PM	18	25
	3 PM	40	32		3 PM	19	26
	4 PM	40	32		4 PM	18	25
	5 PM	39	31		5 PM	17	24
	6 PM	39	31		6 PM	15	22
	7 PM	37	30		7 PM	12	21
	8 PM	35	27		8 PM	12	21
	9 PM	32	26		9 PM	11	20
	10PM	32	26		10PM	10	20
	11PM	31	25		11PM	10	20

4.5 Simulation 2 Results Analysis

To evaluate the efficiency of the Pottery Water Wall in achieving thermal comfort in Luxor, Egypt, the results of simulation 2 are compared to the ASHRAE 55 standards of thermal comfort. The ASHRAE 55 standard for thermally comfortable temperature in winter is from 20°C to 25°C, while in summer the thermally comfortable temperature is from 24°C to 28°C [17].

Figure 11 shows that the Pottery Water Wall achieved a thermally comfortable temperature during the hours from 8 PM to 11 PM, 12 AM to 1 AM, and 8 AM to 10 AM about 37.5 % of the day. The Pottery Water Wall overcooled the building during the hours from 2 AM to 7 AM; however, during this time the outdoor temperature was within the comfort criterion. If the Pottery Water Wall was not operating, thermal comfort should be achieved. Therefore, the range stated earlier could be added to the percent where the Pottery Water Wall can achieve thermal comfort where the percentage becomes 62.5% of the day. However, between 11 AM and 7 PM the Pottery Water Wall did not achieve thermal comfort, and the room's temperature was 2 to 4°C over the upper limit of thermal comfort. Therefore, The

FIGURE 11. Simulation 2 results during cooling session on the 21st of June in comparison to ASHRAE thermal comfort criterion.



Pottery Water Wall achieves thermal comfort for 62.5% of the harshest part of summer in Luxor and does not achieve thermal comfort for 37.5% of the day, but reduces the difference between the upper limit of thermal comfort from 12°C to 4°C , reducing the cooling demand during these hours by 73.5%. The total reduction in the cooling demand during the day is 88%.

FIGURE 12. Simulation 2 results during heating session on the 21st of January in comparison to ASHRAE thermal comfort criterion.

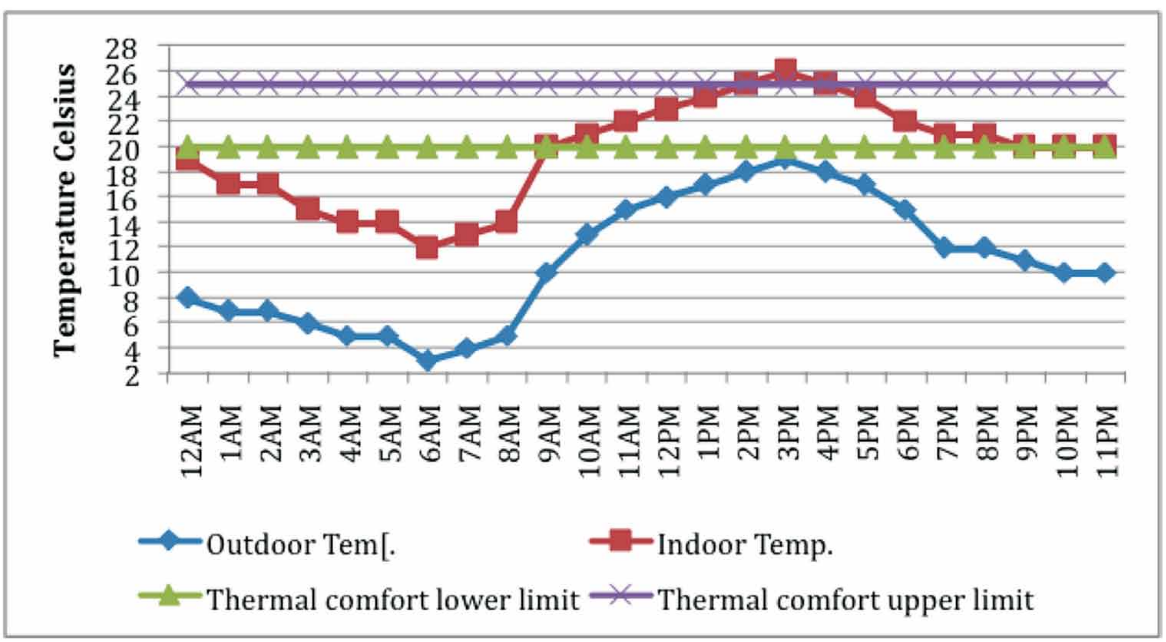


Figure 12 shows the results of the simulation on the 21st of January in comparison to the outdoor temperature and the ASHRAE 55 thermal comfort criterion. The graph shows that the Pottery Water Wall achieved thermal comfort criterion during the hours from 9 AM to 11 PM or about 62.5 % of the day. However, the Pottery Water Wall did not achieve thermal comfort from 12 AM to 8 AM or about 37.5% of the day but decreased the difference between the lower thermal comfort limit and the outdoor temperature from (12°C to 17°C) to (1°C to 8°C). Therefore, heating demand was reduced during these hours 66% from the original demand. The total cut in heating demand is about 88% of the total heating demand on this day.

5. CONCLUSION

From the analyses done on the results the following conclusions were found. First, it was found that a moderate sized (90 X 90 cm) opening has the highest efficiency and any increase or decrease in the opening size and the porous ceramic surface area leads to a decrease in the efficiency of the Pottery Water Wall. A moderate sized opening has the highest efficiency because the larger the opening gets, the increase in the porous ceramic pipes surface area is not sufficient to cover the huge amount of air passing by. Decreasing the opening size reduces the surface area of the porous ceramic and therefore decreases its efficiency in manipulating the incoming air temperature.

Second, the study concluded that the Pottery Water Wall's efficiency in cooling ranges between cooling 4 to 10°C and its heating efficiency ranges between 4 to 15°C according to the design and the temperature of the water.

Finally, the Pottery Water Wall achieved thermal comfort for 62.5% of the days resembling the harshest summer and winter; therefore, the efficiency during the year is more than 62.5%. The Pottery Water Wall covered 88% of the cooling and heating demand of the building during days resembling the harshest winter and summer.

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