THE ARCHITECTURAL INTEGRATION OF PASSIVE SYSTEMS THROUGH THERMAL FLYWHEEL EFFECT WITH EVAPORATIVE COOLING IN SHISH MAHAL, LAHORE FORT, PAKISTAN

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ABSTRACT

There has been much research on the comfort conditions of modern building that used natural ventilation and water bodies as medium of cooling, however much less is known about the impacts of these medium when involved to the traditional and heritage buildings especially the remnants of Mughal Empire. The study reports an ongoing research utilising computational fluid dynamics analysis to study and verify the daily and seasonal impact of passive strategies as constructed in 16th century complexes which had utilised a high degree of complexity in their passive systems through architectural means. Located in one of the forts many quadrangles, Shish Mahal pavilion are built at the north-west corner of Lahore Fort facing to the Ravi River which supplies great source of water and ideal direction to capture the prevailing winds. The architectural integration of water features are interlinked and connected to one building part to another and scattered across the pavilion in a form of certain sophisticated upper and underground water networks via water channels, pools, wells, water walls, basins and water tanks. At the basement, a provision of narrow wind tunnels as a wind scoop to funnel the north prevailing winds into the basement area are integrating with a solid central thermal mass wall associated with various waterwalls on its surface. These intellective driven passive design creating a sort of thermal flywheel effect and effective evaporative cooling strategies. The result highlight that there are significant differences in the temperature drop between the entering and leaving airflow inlets in which the long air that stay inside the basement are proved to induce higher temperature drop as much as 50% and thus suitable to maintain a fluctuation indoor temperature during the summer seasons. By studying the flow and integration of water elements through the complex, the external patterns of wind and pressure distribution around the complex and the transient impact of significant thermal mass and integrated water walls, an estimation of the internal comfort conditions within the complex during spring and summer can be estimated. It is found that the architectural elements had a significant impact and were constructed based on transient effect and such strategies had a significant impact towards comfort conditions under its climate.

Keywords: Architectural integration, passive systems, thermal flywheel, evaporative cooling, computational fluid dynamic (CFD)

1. Introduction

Throughout the world, buildings use 40% of the global energy consumption and responsible of the one third of global greenhouse gas emissions, both in develop and developing countries. In Pakistan, compulsive energy consumptions lead to a serious environmental degradation and expected to further increase because of improving standards of life and increasing number of population. During the last three to four decades, the existing cities such as Karachi, Lahore and Faisalabad spatially expanded because of population pressure and the comparatively smaller towns become the cities which later contribute to the urban heat island (UHI) phenomenon and increase the regional temperature trends. Hence, in order to reduce the emission of greenhouse gases, new approaches like low energy, zero energy and net positive energy buildings are promoted and widely engaged throughout Pakistan.

Before the advent of mechanical refrigeration systems, domestic buildings of the past civilizations relied on the basis of indigenous use for cooling and heating methods such as the adoption of passive systems integrated with intellective driven architectural forms and functions. In earlier discourses, further discussed how sustainable architecture has to reconcile its emphasis on 'performance' with 'design expression' and suggested that combining aesthetics through cultural expression and environmental performance is necessary. It is looking at the past that one comes to the essential goals of sustainability in both form and materiality. Hence it is worth relooking at how past heritage complexes and how such interventions deal with the climatic and environmental conditions without having to consume large amounts of energy.

This paper is only part of an overall conceptualization of a more holistic view of urban water system which can be summarized by a framework that attempts to map the elements that need to be considered in a more holistic scope of research of heritage water systems and how such systems can benefit the current conditions of present cities. Mughal societies at the height of their civilisation, reflected a tendency towards rational forms by imposing 'orthogonal' courtyard and garden forms and patterns in their urban context ,where through the Islamic gardens and city element , the 'grid' 'square' and the 'court' constitute and symbolise a mark of dominance of the Muslim caliph or sovereign on the surrounding nature and populations. These conceptual idealization need to relook a building as a system that comprises of many elements in urban space syntax manifestations. The conceptual of water systems that run inside a building are similar to that in the urban fabric system. Hence water elements were part and parcel of this urban vision of enhanced monumentality and presence; where the use of axis and vistas or common 'nodes' – including pools of still water or pavilions – were utilized to fuse different functions and spaces and thus bring unity into the planning and composition.

Traditional Mughal buildings are commonly built with various passive cooling strategies such as thick wall that characterized by high thermal mass to provides good thermal inertia, provisions of still and moving water bodies to enhanced the evaporative cooling , and natural ventilation by the means of wind-induced ventilation to cool the indoor spaces. All these features can be regarded as intellective driven solutions in seeking an optimum thermal comfortability for the building users. Historical buildings especially heritage buildings have specific characteristics regarding the energy performance behaviour and modeling (Tronchin & Fabbri, 2015) and since there are several studies discuss the thermal performance of modern buildings in Pakistan (Ahmad, Rafique, & Badshah, 2014), (Asim, Dewsbury, & Kanan, 2016) less are conducted on the traditional heritage buildings especially to the Mughals royal residences and complexes.

Shish Mahal pavilion was the apotheosis of Mughal examplary in art and architecture, engineering and urban and regional planning field. The combination of all feat since the beginning of Mugal empire are brought all together are evolutionized and manifested in singular form of architectural marvel. Various elements such as hydraulic engineering, architectural intergration and detailed urban planning can be seen in Shish Mahal where courtyard, water systems, passive design strategies, art and decorations are constructed in articulate manner. However, the most elaborated features of this building lies at the underground chamber where multiple passive design elements can be found and located such as wind tunnels, waterwalls, ponds, cisterns, thermal mass and material properties. Therefore a systematic and deep empirical analysis of these buildings in general and the feasible of Mughal architectural intervention of passive systems solutions worth to be studied and analysed.

This paper presents a description of the CFD simulation used to study the cooling and flow behavior in the basement of the Shish Mahal (Lahore Fort). The aim of the simulation conducted is to model the cooling effects of the water ducts locations and its source, understand the behavior of the capacity of heating and cooling properties of the inner central masonry walls as well as to investigate the flow behavior of the air in the space in order to verify the effectiveness of these passive systems in traditional historical by the means of architectural intervention. ANSYS 17 Fluent was used in the simulations conducted in this study.

2. Literature Review

A passive system design involves the use of natural processes for heating or cooling to achieve balance interior conditions. The flow of energy in passive design is by natural means: radiation, conduction or convection without using any electrical device (Kamal, 2012). Some narration on passive cooling systems explained that the transmissions of heat from the building into the athmosphere with little or no use of mechanical means. Fundamentally, passive systems can be grouped into five main types; daytime comfort ventilation (daytime ventilative cooling), night cooling (nighttime ventilative cooling), evaporative cooling, radiative cooling and ground coupled cooling that uses ground as a heat sink (Carrilho da Graça, Chen, Glicksman, & Norford, 2002).

Past literatures concurred the effectiveness of natural ventilation adaptive method in historical buildings via dynamics simulation such as in Lahore where the maximized wind-induced ventilation by sitting at the ridge of building perpendicular to the summer winds. Further analysis on ventilative stack effects is capped by a metallic dome which gets heated up and due to pressure differences, it creates a suction effects that draws the air of the entire building to let it go out at the top and offering a 20ºC in summer and 10ºC in winter, hence suited the best temperature to human comfortability (Khalid & Uppal, 2011). Ventilative cooling by wind relies on the wind force to produce pressure differences between the interior and exterior building, which causes the internal air movement and heat removal from the interior (Chenvidyakarn, 2007). He further elaborate with the indoor airspeed of around 1.5m/s to 2.0m/s, ventilation can provide comfort in regions and seasons when the maximum outdoor air temperature does not exceed about 28˚-32˚C but it is depended on the humidity level and the acclimatization of the population.

In hot arid climate, it is necessary to control the flow of ambient air inside the courtyard in order to maintain the internal temperature of the building. The correlation between aspect ratio and cross ventilation is crucial in courtyard housing (Das, Coates, & Gabbard, 2005). In his findings, aspect ratio calculated as the sum of area of the courtyard floor over the average height of the surrounding wall. In hot humid climate, design consideration for thermal comfortability for courtyard design lies in the building proportion by making the courtyard deeper with thicker surrounding room wall.

As for the thermal mass, it is the ability of high-density materials such as brick and stone to absorb heat, retain it and release it slowly overtime which function as a heat sink during the day by absorbing internal gains and helping to moderate the temperature fluctuations within a room. This process is known as thermal inertia and sometimes are called thermal flywheel effects and in the summer seasons, thermal mass helps to attenuate the outdoor temperature peak and to keep the internal conditions within the comfort range by absorbing the excess heat (Gagliano et al., 2014). During the winter, all solar radiation and heat gains that stored inside the wall during the day are slowly released into the indoor environment at later time. Fundamentally, the higher thermal inertia of the building will results slower rate of indoor temperature fluctuations.

Provisions of water surfaces to modify the microclimate of the surrounding area has been highlited in previous study where reducing the ambient air temperature by evaporation or by the contact of hot air with the cooler water surfaces such as fountains, ponds, streams, waterfalls or mist sprays (Geetha & Velraj, 2012). In recent discource, a dynamics simulation of new bred of waterwall devise has been engaged to analyse the ability of evaporative cooling effectiveness where a pottery water wall consisting of waterwall and porous ceramic pipes tested in Luxor, Egypt. The devise achieved thermal comfort for 62.5% of a day resembling extreme summer and achieved thermal comfort 62.5% of a day resembling extreme winter (Moustafa & Aripin, 2014). This is however taken into consideration that the devise applied to the building façade facing directly to the sun exposure in which differs to the one that found in Shish Mahal where the water wall assembled deep inside the building. Due to this circumstance, the study is worth to be investigated and further exploration in empiricaly basis to its ameroliation of thermal sensation under the climate of Lahore, Pakistan.

In the present day, provision of water as a cooling agent has been empirically proven in various literatures. According to (Bagneid, 1989), during a one week period, the courtyard with the evaporative spray had a slightly cool to cool Predicted Mean Vote (PMV) 15% of the time. The results show the courtyard as being an effective microclimate generator. Apart from that, an integrated passive cooling strategies that apply in an enclosed space also play significant role in mitigating the heat retention where a retractable shading over the courtyard, watering the patio's absorbent floor (i.e., evaporative cooling), opening the windows for night ventilation, and high thermal mass contributed significantly to the passive thermal cooling of the house (Reynolds & Carrasco, 1996). These investigations agree that architectural intervention play crucial roles in uplifting the efficiency of wind-driven ventilation cooling effects.

3. Case Study

Shish Mahal Pavilion

The case study concerns a historic royal residential building situated in the historical city of Lahore Pakistan (lat 31°52'N, long 74°40'E.). Located in one of the forts many quadrangles or courtyards, Shish Mahal pavilion are built at the north-west corner of Lahore Fort facing to the Ravi River (Figure 4). Historically, Shish Mahal courtyard development are set under the rule of Mughal ruler Shah Jahan (1627-1658) and reserved as a royal residence for imperial families and royal courtiers.

The courtyard was built based on a proportional rectangle with dimension of 38m x 40m and surrounded with single storey open loggias to the east, west and south of the courtyard with height approximately 4.9m to 6m from the floor (Figure 5). Overall, the building consists of four floors above ground and constructed with high mass structural envelope and rich uses of mortar layer with the thickness almost equal to the height of the construction unit. A single construction unit consists of typical Mughal brick sizing of 203.2mm x 101.6mm x 330.2mm with almost 25.4mm thick of line mortar (Raheem & Tahir, 2008). As for the Shish Mahal pavilion, a two storeyed semi-octagonal building stands at the north side of the courtyard with the height of 6.38m up to 9.77m if to include the reinforced parapet wall with double volume interior hall dominated at the centre. The building façade has many openings facing to the north (facing riverfront) and south (facing courtyard) which allow the north prevailing winds to enter and ventilates the courtyard as well as to the four openings at the basements.

Like all Mughal quadrangle or courtyard design, so often designed with central pool dominating at the center, the shallow circular pool of Shish Mahal courtyard appeared very differently from others. The pool has a width of 16m x 16m and at a depth of 15cm with central decorated platform (mahtabi) in the middle. It is decorated with pietra-dura using semi-precious stones such as agate, jade, carnelian, lapis lazuli and chalcedony. The courtyard is subdivision into four quadrants of four narrow water channels where the southern channel acts as a sole supply of water to the central shallow pool. The rest of the channels funnel the overflow water from the central pool into the subterranean living chambers via Chaddar (waterwall).

Figure 1: Illustration of Lahore Fort from aerial view showing various locations of water structures scattered throughout the Fort

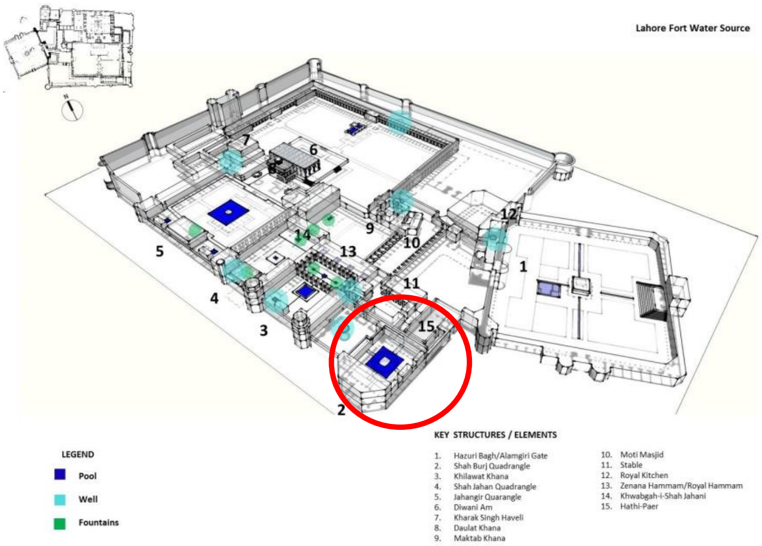
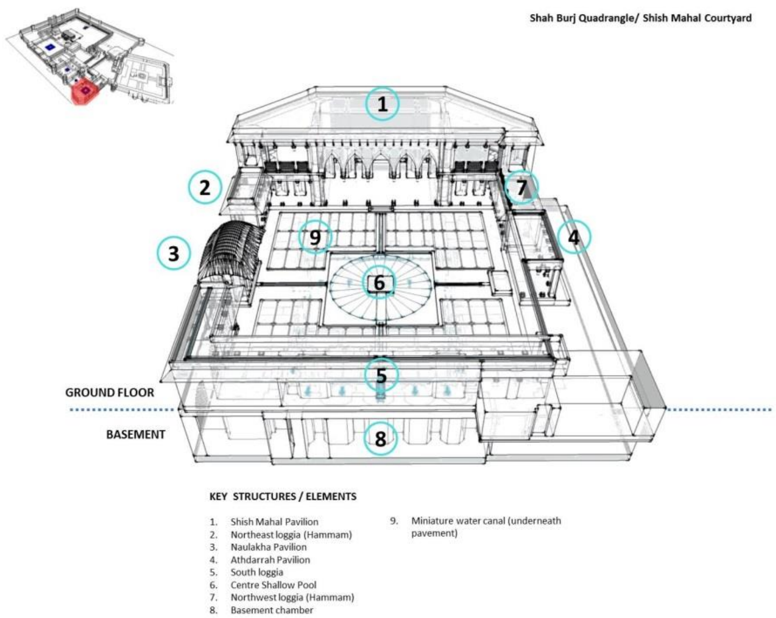


Figure 2: A 3D illustration of Shish Mahal courtyard and surrounded buildings where Shish Mahal pavilion stands at the north east side of the quadrangle



The basement

The basement however is specially designed with various underground wind tunnels and openings, waterwall chambers and secret Royal passages which led to other part of the fort. The basement ceiling height can reach approximately 3m but some part extended up to 6.9m. Thickness of the basement masonry wall exceeds from 3.6m to 4.7m deep at the northern wall which designed to give a long lasting structural stabilize (Khan, 2011). The basement chamber is dominating by a solid central wall that has 16 niches and waterwall or chaddar on it.

Figure 3: Underground basement floor plan Underground basement floor plan

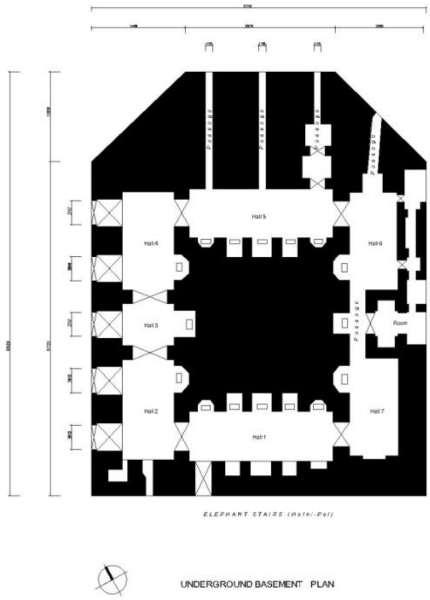
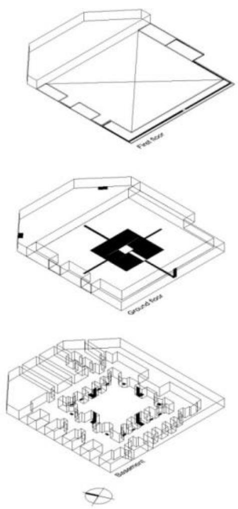


Figure 4: Exploded 3D architectural diagram of the three floor levels of Shish Mahal courtyard

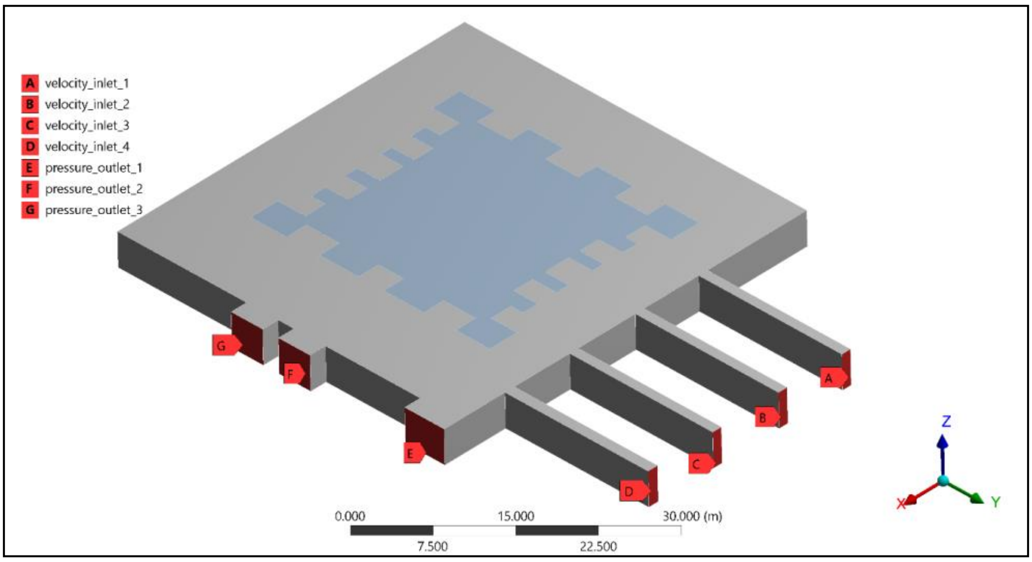


4. Methodology

Overview
The Numerical analysis consists of a CFD simulation of basement of the Shish Mahal (Lahore Fort). This is used to characterize the behavior of cooling behavior the space as well the as the air flow performance.

Geometry Model
Accurate modelling of geometry is essential for getting accurate, representative and verifiable results. The geometry has been modeled according to the dimensions of the measurements of Shish Mahal (Lahore Fort) Basement and underground water ducts locations and its sources. The snapshots systematically converted via CAD software to a model usable by the ANSYS mesher.
Two models were created; a short model that only takes into account the central cooling brick walls, while the rest of the geometry of the basement has been simplified to include the air that flows inside it. 4 inlets and 3 outlets were specified according to the flow behavior of air in Lahore as shown in figure 1.

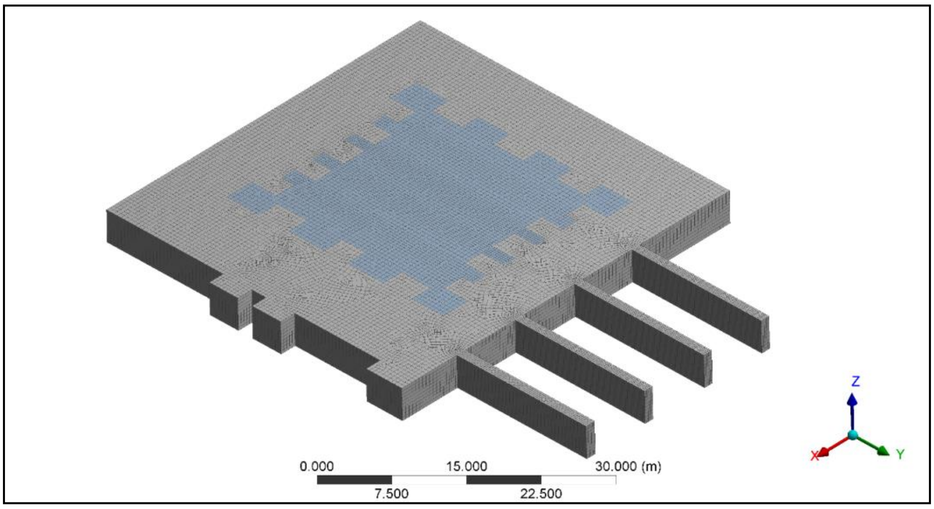
Figure 5: Geometry model



Geometry Meshing
The meshing of the model is conducted using a tetrahedral patch confirming method. It is a Delaunay tetra masher with an advancing-front point insertion technique used for mesh refinement. This method is used to ensure a high quality surface mesh is generated (ANSYS, 2014). The meshing application determines a suitable number of divisions for the edges on the boundary face automatically.

Using the advanced sizing function on curvature and proximity, a curvature normal angle of 12° is specified. A minimum element size of 0.008 m and maximum face size of 0.35 m are specified. A mesh growth rate of 1.1 is specified to ensure uniformity of the mesh across the geometry while other parameters were left to their default settings.

Figure 6: Mesh of modelled geometry



A mesh with an element count of 110680 with 132341 nodes is generated by the mesher. The meshed model shows a mesh skewness of 0.0507 with a standard deviation of 0.009 that is categorized as “excellent” and an element quality of 0.927 with a standard deviation of 0.06 that is categorized as “very good”. The skewness is a value that indicates the quality of the cell size (Bern & Plassmann, 2000). A mesh independency study has also been conducted.

Physical Model
For this simulation, the energy model is enabled. A viscous realizable k-ε Model is utilized for viscous flow modelling, fully buoyancy effects are enabled. This model has been demonstrated to give superior performance and has shown substantial improvements over the standard - model where the flow features include strong streamline curvature, vortices, and rotation. This improved accuracy is said to be beneficial for complex engineering flows including those with streamline curvature.

In this simulation, the standard 'Wall Treatment' has been chosen for the 'Induced Roughness'. The effects of buoyancy have also been selected as one of the parameters for solving the model. This result in the calculation of energy produced due to buoyancy and accounts for it in the k and ε equations that are part of the Reynolds stress model.

Table 1: Physical Model properties

Property	Action
Energy	On
Turbulent Equation	Viscous - realizable k-ε Model, Standard Wall function
Near Wall Treatment	Scalable Wall Functions
Other options	Full buoyancy effect
Mesh Interface	Coupled wall Interface

Table 1 shows the physical equations used in simulations conducted in this simulation. The quations for momentum, mass and energy are standard equations.

Material and Model Properties

Standard Air thermal properties are used for this model while the wall properties are set to that of dense bricks as specified by Table 2.

Table 2: Physical Properties of dense bricks

Property	Value
Density (kg/m^3)	2400
Specific heat (j/kg.k)	750
Thermal Conductivity (w/m.k)	0.67

Provided pressure-velocity PICO scheme algorithm was selected for solving the model due to its ability to perform full pressure-velocity coupling. This solver offers some advantages over the pressure-based segregated algorithms with transient flow calculations. The pressure-based coupled algorithm provides a more robust and efficient single phase implementation.
Weather data for the month of August was retrieved from the Lahore Civil/Military airport and simplified to that of Table 3. The data is used to specify the forthcoming water cooling calculations as well as the input velocity to the model.

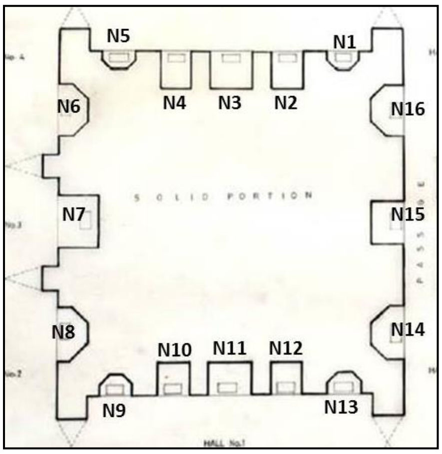
Table 3: Weather data for Lahore (August)

Property	Value
Average high temperature	35 °C
Average low temperature	27 °C
Humidity	65 %
Dew Point	26 °C
Pressure	1004 mbar
Wind speed	9 km/h or 2.5m/s

Water Cooling

There are 16 water ducts locations and its sources specified in Table 3.

Figure 7: Location of water sources on every niche at the central masonry wall in the basement



The amount of evaporated water from one water source can be found via Equation 1.

$$g_s = \frac{\Phi A(x_s - x)}{3600}$$

Equation 1

Where

Φ = (25 + 19 v) = evaporation coefficient (kg/m^{2}h)
x_s Humidity ratio in saturated air which is 0.01982 kg/kg at 25c
x Humidity ratio in the air (kg/kg) which is found from Mollier's diagram

The heat lost during the evaporation process can be calculated via Equation 2 which gives the amount of heat lost or absorbed when any amount of fluid is evaporated.

$$q = h_{we} g_s$$

Equation 2

Where

q is the heat lost (kJ/m^2)
h_{we} is the evaporation heat of water (2257 kJ/kg)
g_s is the amount of evaporated water

heat lost from the wall surface during evaporation process is calculated and then applied as negative flux on the 16 water surfaces during process time via Fluent UDF (User-defined functions) and scheme programming.

5. Results And Discussion

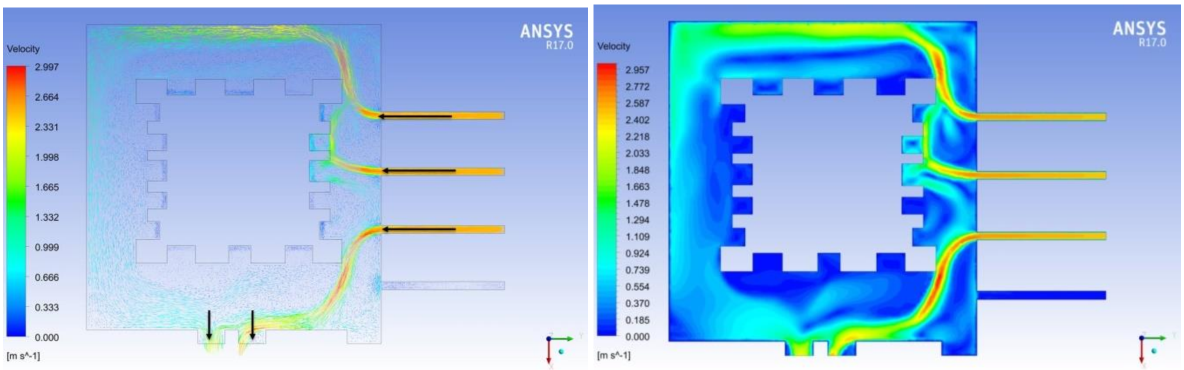
Overview

The results detail the velocity and temperature profiles of cross-sectional planes across the geometry. Attempts are made to identify regions cooling regions and amounts.Two scenarios are tested in this study. The result illustrate the patterns and behavioral of airflow and temperature of the basement taking account on the availability of the waterwall on each niches on the surface central wall.

Airflow Profile

Air was set to enter the model at a constant velocity of 2.5 m/s (9kmh) in FLUENT in order to simulate the air flow entering the basement of the fort with the outlet set to pressure outlet, ensuring that backflow is possible. The results show that adequate air flow happens in the basement while it is also apparent a large percentage (51%) of the air exits the system quickly without much circulation via the first pressure outlet, 31% and 17% exit the system by the next subsequent outlets.

Figure 8: Velocity profile across the basement (vectors and contour results)

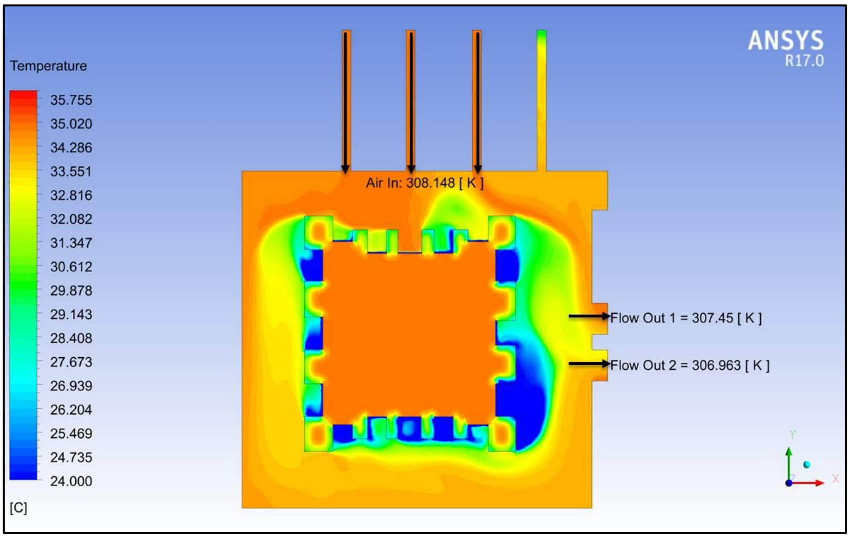


Temperature Profile

The temperature profile shows that cooling happens due to the water surfaces at all points, however, the lack of mixing for a large percentage of air flow in the system leads to low amounts of overall cooling in the exiting air.

The study shows that during the middle of the day when the air has a maximum temperature of 25º C, Air entering the system at the maximum average temperature 35°C and exits the system at an average temperature of 34.1°C. Colder air exits the system at pressure outlet 3 at a temperature of 33.5° C.

Figure 9: Temperature Profile across the basement



The results show an evidence of cooling capabilities in the in the basement of the Shish Mahal (Lahore Fort). Cooling was found to be evident during both night and day cycles of the simulation and shows the cooling can happen by up to a temperature difference of 2 degree Celsius between the entering and leaving air. Further analysis may be beneficial to analyse the cooling behavior during different weather patterns and wind direction.

Figure 10: Temperature vs time (flow in and flow out)

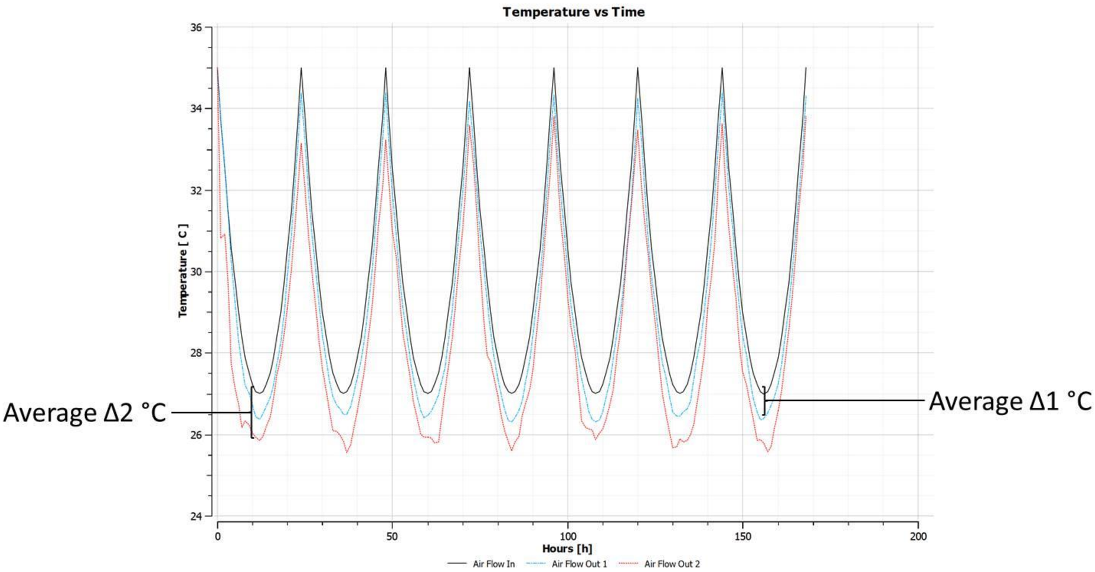
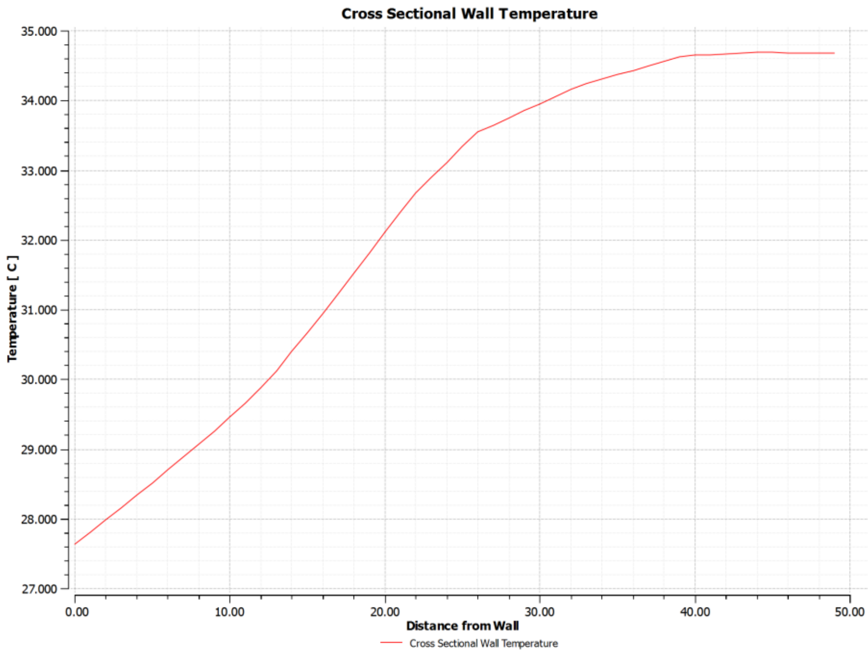


Figure 11: Cross sectional temperature of central wall (distance from wall in cm)



The temperature versus time graphs (figure 11) show the cooling behavior of the air during the day-night cycle, where it is evident that air is cooled during the whole cycle. It is also observed that the cooling of air is highly dependent on the duration of time that the air spends near the cooling walls as it is shown that air that quickly escapes the system via pressure outlet 1 is cooled 50% less than air exiting via the second outlet.

In regards to the cooling behavior of the central wall, it is observed that the inner temperature of the brick structure is highly stable and that latent cooling penetrates to a distance that is maxed at 50 cm (figure 12), probing the central wall brick structure further in only yields stable temperatures that are not changed during the day-night cycle.

6. Conclusion

The study presented in this paper investigates by the means of dynamic simulation, the thermal mass performance and evaporative cooling effectiveness of the basement chamber of Shish Mahal located in Lahore, Pakistan. The CFD study was conducted with the weather data for the month of August (summer). The results show that the day-night cycle as well as the latent cooling from water walls induces a considerable amount of cooling.

The results detail the behavior of air flow as well as the cooling behavior of the air in the basement. The air flow behavior shows that air flowing in the basement has the tendency to follow the shortest route out of the basement; this has proven to show that the cooling amount is heavily taxed by this behavior. Further testing shows that the long the air stays in the basement induces much higher temperature drops (up to 50%). The study also explains how the cooling conducted in the basement. Further studies of the structure in the future should take into account the cooling behavior when wind direction and magnitude have different variables. Since the simulation are conducted on the hottest day of the year which on the month of August (summer), it is aware that winter scenario is also needed in order to further analyze the efficiency of central thermal mass in terms of its thermal flywheel effects and thermal inertia.

In terms of architectural integration, it is possible to conclude that a balance between optimum internal temperature, evaporative cooling and thermal mass can be achieved with a holistic design approach. The good architectural intervention of this building that it allow better indoor evaporative cooling to work more efficiently by constructing wind tunnels at the façade that facing the prevailing winds direction and constructing central thermal mass that functioning to play significance role in reducing the indoor temperature. Although region with design wet bulb temperature higher than 24°C are places where evaporative cooling strategies may not be worked with great efficiency, the present CFD of evaporative cooling and thermal mass proven otherwise and may promote good thermal comfortability with architectural intervention.

The studies can suggest the idealized spatial system that can be used in urban design and complexes which later became a methodological and abstraction tool of sustainability to suit the modern contemporary world.

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