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COUPLING THERMAL MASS AND WATER SYSTEMS AS URBAN PASSIVE DESIGN IN HOT CLIMATES

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ABSTRACT

The impact of water in buildings is studied as a combination of vertical walls and horizontal pools that creates a combined passive cooling system for public spaces in hot climates. The paper draws from traditional water-based systems principles and forms in Mughal architecture, with the aim of studying its thermal cooling impact using CFD. Due to rapid urbanization in cities, there is a heightened demand for cool, dry comfort yet energy use can be saved by focusing on the cooling of workplace spaces while public areas are naturally cooled to reduce the carbon lock-in effects of cities. Selected sections of 16th and 17th century Mughal complexes are analysed in terms of its combination of both thermal mass (thick, high density walls), water pools, water walls and channels. The study initially looks at water to ground ratios of different Mughal gardens and enclosed courtyards, the overall integration of pools, channels, and water walls in past forms. More importantly, it analyses the impact of the coupling of thermal mass and water elements in a passive system within an infrastructure to achieve almost zero reliance of non-renewable energy for its public areas.

Keywords: urban water strategies, passive cooling, water infrastructure, sustainable low energy cities, thermal mass.

INTRODUCTION

Cities and urban centers in hot regions-both the tropical belt and hot arid zones are modern cities that suffer from long term carbon lock-in effects due to escalating air-conditioning use and a rapid rate of urbanization and population growth. There is rising comfort expectations in an urbanised lifestyle and this increases demand for year-long air-conditioning comfort.

As cities grow, there are various indoor and semi-indoor spaces in public areas that are fully air-conditioned and strategies must be studied of how to reduce energy use in these non-critical areas. To reduce the use of sealed environments and air-conditioning in public spaces - ground floor walkways, plazas and lobbies in hot climates, can be cooled by water-based and thermal mass strategies such as water walls, channels and ponds. This should be optimized as part of a new 'water urbanism' in order to reduce energy use for future low carbon city development. Recently, researchers [1] have called for concepts such as the 'water sensitive city' to enable a transformative change in present cities. Until today, such conceptualizations and solutions have served merely as a theoretical framework. The role of water systems seen as urban systems has both socio-ecological and socio-cultural dimensions rather than merely engineered solutions.

Traditionally, water elements have essentially two main purposes; 'aesthetic' and 'functional'. In Islamic civilizations, water has a spiritual dimension and elements of water architecture have long been integrated into the growth of such civilizations. The growth of Islamic cities had during the medieval centuries had focused on hot arid environments in which water was a part of both passive cooling strategy and an everyday necessity. Water provide psychological, visual, auditory, and tactile effects, which are primarily perceived by the senses, and affects human psychologically rather than merely visually and physically [2].

WATER SYSTEMS AND THE MUGHAL ARCHITECTURE

Mughal gardens and its water systems have been called an 'aesthetic distillate' of the past Mughal civilizations due to its agricultural and water-based economy and civilizations [3]. As urban forms, these have evolved into variations of octagonal pools and gardens within plazas and courtyards. The archetypical Persian Chaharbagh is a refinement of such water systems, that had developed alongside the evolution of its arts and architecture and these had expanded into multiple-form and rescaled urban forms.

Figure-1 is an outcome of an analysis into a range of estimation of the urban water to ground elements of different Mughal gardens within a defined boundary. Its water to ground ratio is estimated through calculating its water surface area while represent the amount of exposed water and ground area that dwell within a specific boundary.

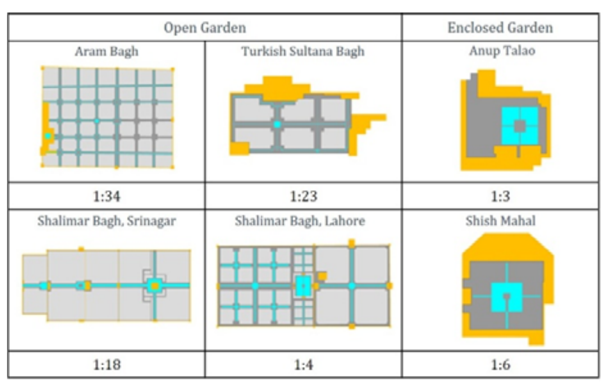

Figure-1. Charbagh (gardens) morphology configurations and its water to ground ratio.

VOL. 12, NO. 16, AUGUST 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

The spatial morphology varies in either open space or enclosed space yet its ratio is hypothetically linked to its comfort level achievement which depended on the size of its water pools and an enclosed boundary with less exposure to solar radiation and with wind velocity especially during the summer season.

The analysis found that Shish Mahal courtyard's water to ground ratio is estimated at approximately 1:6, interestingly, the research also found that this water to ground ratio is similar to that of Masjid Negara in Malaysia that is known for its cool internal spaces without the utilisation of full air conditioning in its prayer areas.

HYDRAULICS - WATER SYSTEMS INFRASTRUCTURE IN THE MUGHAL CIVILIZATION

While gardens are essentially 2-dimensional elements, the function and forms of architecture are 3-dimensional entities within 3-dimensional urban cities. Hence, this paper has studied an example of such 3-dimensional system by combining its evaporative cooling strategies with its wind-induced mechanism. The two complexes of the same civilization are the FatehpurSikri in Agra, India and Shish Mahal in Lahore Fort, Pakistan;

FatehpurSikri, Agra-India

FatehpurSikri is studied as an example of how the Mughals had built their complexes and gardens near the rivers or water sources and hence essentially able to draw both water and thermal cooling benefits from a systematic hydraulic and irrigation system that includes the use of gravity flow and elevating the water via multiple distribution mechanisms. This mechanism had catered for the provisions of water in raised occupied structures, aqueducts and baolis (stepwells) in the civilization. In FatehpurSikri, for example, water is lifted from one level to a multiple elaboration levels or tiers as the prime sources of water came from the baoli (stepwell) located down the ridge as shown in Figure-2.

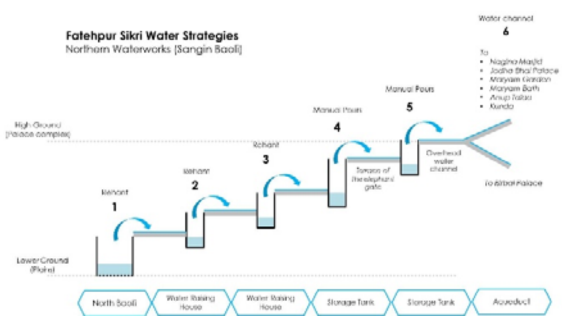

Figure-2. Illustration of water raising system mechanism via multiple water raising houses (enclosed water raising structure) and aqueducts at FatehpurSikri.

According to [4] the device for elevating water is based on an evolution of the Persian rehant system, or the water wheel. Chambers within the baolis (stepwells) and water raising houses contained wheels with shafts driven either by humans or cattle. These wheels in turn rotate the shafts that drive a belt of earthenware water-filled pots, up to the next stage of the waterworks. Figure-3 shows an elaboration of the rehant system frequently seen in the medieval cities, and contemporary India village wells and in agriculture systems and often cattle were used to raise water from the well to upper ground level.

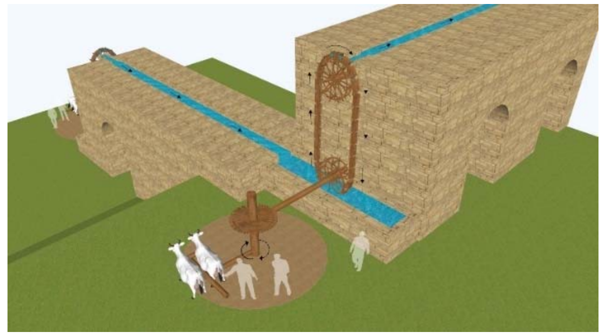

Figure-3. Conceptual illustration depicting rehant (water wheel) driven by cattle to lift water to higher ground associated with aqueducts.

Shish Mahal of Lahore Fort-Pakistan

Lahore Fort, Pakistan is a citadel spread over approximately 50 acres and built by Mughal Emperor Jalaluddin Muhammad Akbar in 1575 and resumed by Shah Jahan in 1632. The Shish Mahal courtyard is located inside the quadrangle section at the northwest corner of Lahore Fort which served as the residence of the Empress. In this courtyard, water is used both as an integrated hydraulic system here and coupled with a series of thick masonry walls. The systems ventilators within these walls were designed to provide occupant coolness in public spaces such as open plaza and courtyards. Miniature ducts ran underneath the courtyard floor and constant flow of water kept the floor incessantly cool.

According to [5] these ingenuous mesh of ducts under the paved floor are interconnected to each other and funnel into a certain overall direction and water used for this cooling system are filtered before it was inducted into the ducts. The basement space is designed with full passive strategies with the water-thermal coupling through several water walls features and miniature ponds aligned systematically to provide an ambient coolness particularly during the summer seasons as shown in Figure-4.

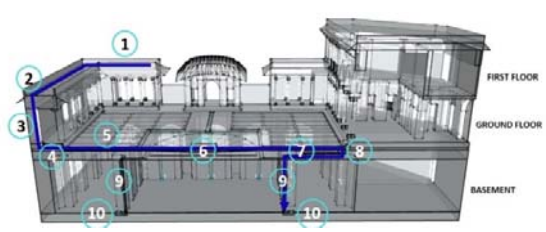

Figure-4. Illustration of Shish Mahal and cross sectional diagram portraying various waterworks designed within the courtyard boundary and continuous flow of water to the basement area starting at the rooftop.

VOL. 12, NO. 16, AUGUST 2017 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

To the north of this basement was a long narrow tunnel that acts as a wind catcher of the north prevailing winds which later enhance the quality of cool air ventilation throughout the chamber itself as shown in Figure-5.

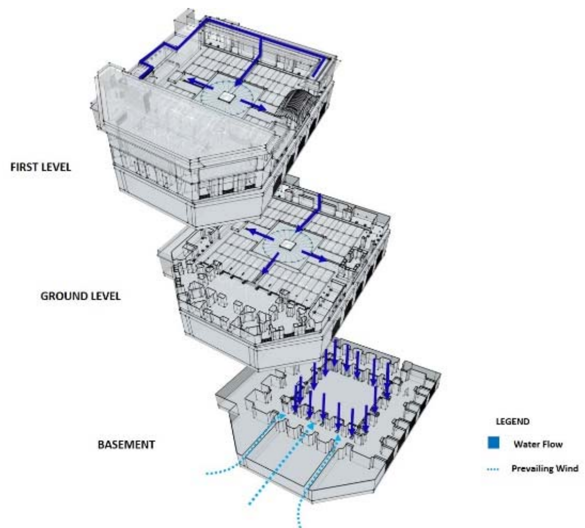

Figure-5. Exploded diagram expose the conceptual water flow illustration at three floor levels and location of narrow wind tunnels at the basement.

THE COUPLED WATER AND THERMAL MASS SYSTEM-CFD ANALYSIS

The outcome of the water-thermal mass coupling on the thermal comfort of the internal space is studied and analysed by a computational fluid dynamic simulation. The Shish Mahal basement is located at the first floor of the three levels palace complex in the northwest corner of Lahore Fort was built and used as a retreat chamber during the summer season by previous Mughal emperors. The spatial configurations of the basement consist of a series of high vaulted halls, wide corridors, wind tunnels and a solid central masonry mass at the centre. These wide corridors are interconnected and lead to many other private chambers that located at the southeast part of the basement. The central masonry mass acting as a sensible thermal storage of the basement and capable to give a high thermal inertia impact to the building component [5] and had a dimension of 26m in thickness. As for the envelope, the surrounding thick external walls are pierced by wind channels and at some point, the thickness can reach more than 4.7m deep especially at the northern wall. The three wind channels facing to the northeast wall are purposely designed to capture the prevailing winds that come from the Ravi River that once flowed paralleled to the palace northern wall. The central thermal mass is fused together with a series of 16 decorated water walls that built on its surface which located exactly beneath the courtyard pond above the basement. The water is received from the overflowing water from shallow pool at the above courtyard and funnel down to these 16 water walls simultaneously before it channelled away to nearby storage well for collection.

This is as shown in Figure-6 which is used as the subject of analysis. A model with total grid mesh of 110,680 with boundary condition is built and the CFD simulation runs with an initial velocity of 2.5m/s. The results are obtained and divided into three parts; air velocity, indoor temperature, and temperature across the central masonry thermal mass. Selective months was subject to simulation using Lahore climate data and these are set to August to focus on for its summer seasons scenario and the results illustrates the patterns and behavioral of airflow and temperature across the basement area. According to [6], recommended thermal comfort conditions for indoor temperature generally range between 19 ˚C to 27 ˚C, however a more specific range can be determined from the standard but depends on relative humidity, season, clothing worn, activity levels and other factors.

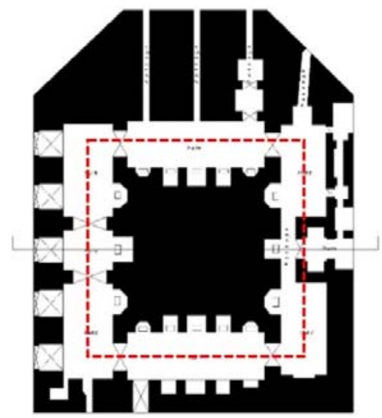

Figure-6. A floor plan of Shish Mahal basement and the location of thick central masonry mass (thermal mass).

The results are shown in Figure-7 and Figure-8 highlights the different behavior of air velocity patterns based on the inlets flow configurations which flow at a constant velocity of 2.5m/s and the temperature analysis across the central masonry wall respectively.

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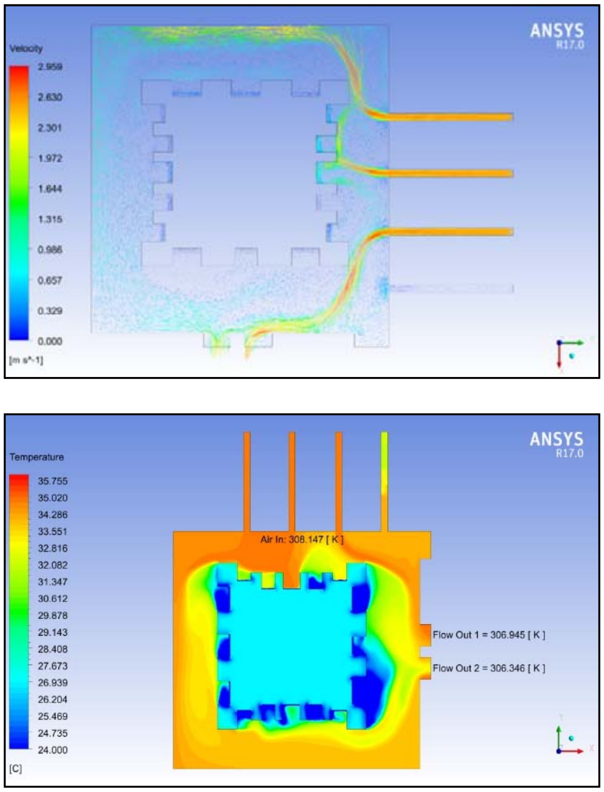

Figure-7. Airflow and temperature profile with entered air velocity of 2.5m/s.

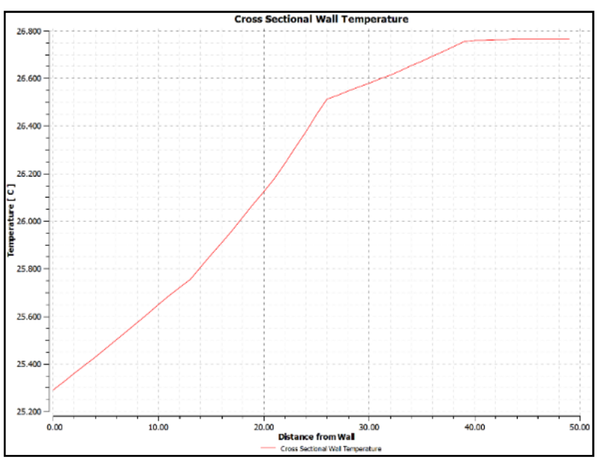

Figure-8. Temperature analysis across the central masonry wall.

The results show that adequate air flow happens in the basement for all cases 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 at high air velocities, it's observed that the air cools a significant amount for both air velocity cases.

The temperature profiles show that cooling happens due to the availability of 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 exit air. Cooling was found to be proven both night and day cycles depending on the entering air velocity at the basement. While a cooling of 2 degree Celsius is considered significant when maximum air velocity of 2.5 m/s, it is expected air velocity entering the basement during practical weather to be significantly lower and in the range of 0.1 m/s to 0.7 m/s.

In regard to the cooling behavior of the central wall, it is observed that the inner temperature of the central masonry wall is highly stable and that latent cooling penetrates to 50 cm into the wall. Probing the central masonry wall structure further in only yields stable temperatures that are not changed during the day-night cycle. This is consistent across different air velocity tested.

CONCLUSIONS

Sustainability in cities requires a paradigmitic shift from a complete reliance on air-condtioning, especially for public and regularly occupied spaces. This paper is both a conceptual and empirical study to analyse the potential of a more integrated approach. Water systems need to be built into urban systems and infrastructure not merely as hydraulic systems but as both aesthetic, cooling and functional system-conflating both environmental and socio-cultural functions.

The conceptualisation of sustainable urbanism, urban design and architecture in hot climates must relook into how water systems have multi functional to urban life. This must begin with a study of past heritage complexes as a starting point. Urban water systems and urban-water design must reconceptualise towards a more holistic water urban approach. There must be a transformative change and water must be integrated as both 2D and 3D elements while urban water systems should no longer be considered as 'left over' infrastructure but designed to optimise both in its thermal and cooling effects with physical structures. Such elements must be integrated holistically in the 3-dimensional concepts of architecture and urban design at the onset of design of urban spaces and its planning.

Water systems also evolve with cultural values with symbolic meaning integrated into any architectural solution. These should include not only looking as 'water systems' and elements per se, but should be reconceptualised into 'water-garden' systems, the garden landscape, the alignment with waterfronts and the symbolic and socio-historical meaning of water elements, including the strategic and symbolic significance of water.

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ARPN Journal of Engineering and Applied Sciences

REFERENCES

[1] Booth, N. K. 1989. Basic Elements of Landscape Architectural Design (1st ed.). Illinois: Waveland Press Inc.

[2] Ferguson, B. C., Frantzeskaki, N., & Brown, R. R. 2013. A strategic program for transitioning to a Water Sensitive City. Landscape and Urban Planning, 117, 32-45.

[3] Petruccioli, A. 1998. Rethinking the Islamic Garden. In J. Coppock & J. A.Miller (Eds.), Transformations of Middle Eastern Natural Environments:Legacies and Lessons (103rd ed., pp. 349-363). New Haven, Connecticut: Yale University Press.

[4] Sumra, A. 2012. Fatehpur Sikri; ciudad de aguas - Casiopea. Retrieved April 27, 2016, from http://wiki.ead.pucv.cl/index.php/Fatehpur_Sikri;_ciudad_de_aguas.

[5] Navarro L, de Gracia A, Niall D, Castell A, Browne M, McCormack SJ, *et al*. Thermal energy storage in building integrated thermal systems: a review. Part 2. Integration as passive system. Renew Energy. 2016; 85: 1334-56.

[6] Schoen, L. J., & Alspach, P. F. 2013. ASHRAE standard 55-2013: Thermal Thermal Environmental Conditions for Human Occupancy (ANSI Approved) (Vol. 2013). Atlanta, GA: American Society of Heating, Refrigerating and Air- Conditioning Engineers. http://doi.org/ISSN 1041-2336.