Evaluating the Performance of Naturally Ventilated Brick and Lime Domes and Vaults in Warm-humid Climate in South India

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ABSTRACT

India has a rich tradition of passive architectural design practice. There has been, however, little effort to study these design strategies to evaluate their effectiveness. This study analyses the climate responsiveness and thermal performance of domes and vaults in brick masonry.

The study compares the performance of hemispherical domes and segmental vaults in a residence-office building for indoor conditions measured on hourly basis for one year. The study gives the necessary quantifiable performance of domes and vaults constructed using low-cost, local materials as an effective energy efficient design strategy that may be easily adopted as a practice.

INTRODUCTION

Vaults and domes appeared in Auroville in 1982 as an answer to the cement shortage after the oil crisis of 1979. Imported cement from Vietnam and South Korea was being sold in the black market in India at a high price. The labor intensive and high thermal mass construction of domes and vaults in local country fired bricks with lime mortar seemed to be the ideal alternative to RCC roofs.

They can be a good example in today's context of high energy intensive construction techniques. While addressing the increasing demand of housing in India with the use of natural materials, innovative techniques and engagement of local craftsmen as a cost effective, culturally, socially and economically sustainable means; they also provide a continuum of traditional knowledge and employment generation in the region.

An example of a residence-cum-office complex using these techniques was chosen for this study. From the two residences, we have concentrated on the right side of the complex (refer photo – fig 1), which consists of three domes and three vaults, since two of these domes provided us an opportunity to study different ventilation systems – one with an air vent and one with aluminium wind extractor *(Dome 2; Fig 4).*

Figure 1 Mukuduvidu Complex. Southern facade, 1992

CONTEXT AND CLIMATE

Auroville context (warm-humid climatic zone of India):

Latitude:12^{o} N | Longitude: 80^{o} E | Altitude: +60 MSL Winters (Nov – Feb) : 21 ^{o}C to 32^{o}C Summers (April – July) : 28^{o}C to 41^{o}C	Daily radiation received: 4 to 7 kWh/m (peak – 1 kW/m² at noon) Annual average rainfall : 1,200 mm North-east monsoon (Oct – Dec) - approx 60% of the annual rainfall South-west monsoon (June – Sept) - approx 20% of the annual rainfall

Alternating land and sea breeze provide reprieve from the hot and humid climate. Relative humidity varies from 60% to 90% throughout the year and wind velocity varies from 0 to 8 m/s with 1.4 m/s annual average (AV weather station data / CBERD project).

Case study. Mukuduvidu Complex. Fact File :	
Year:	1990 - 1992
Usable area:	96m^{2}(ground floor); 48 m^{2}(first floor); Total: 144 m^{2} (this represents the part under study only)
Architects	Poppo Pingel and Mona Doctor-Pingel
Passive Strategies	North-south orientation | thermal mass – 0.22 m load bearing low fired country brick with lime mortar and plaster | 1.2 m overhangs in the south and north | wind exhausts for domes, high ceiling with vault structure to allow for ventilation under the roof | maximum large openings on the south, less large on the north side (rain direction, sun in the summer) with minimum opening of the east and west side | domes are covered with reflective white broken china mosaic | Extensive landscaping with large trees on the west and north, water bodies and Zen sand garden to the south.
Construction methodology:	Up to 4 m spans for vaults and 5 m diameter for domes are economical from structural and functional point of view with this construction method. Vaults were constructed by a wooden sliding shutter of 1 m width. The flat roof achieved by a vaulted roof also allows a terrace for drying and sleeping during the hot summers. Local unskilled labor can be easily trained in the simple masonry required for domes and vaults. A single casuarina pole fixed in the center with a rotating arm acted as a guide to create a hemispherical dome and within a week, the roof was created (Fig. 7.1). All construction work was done manually.
Principles of Baubiologie Employed	Baubiologie (Building Biology) - the study of the impact of built environment on the health of the people and the application of this knowledge to the construction of healthy homes and workplaces – was applied in this building | Concerns of electro-magnetic fields taken care of by a judicious design of electrical layout | Use of natural materials | Bio concrete for the RCC beams, specifically made with hand-cut limestone chips as aggregate | Waterproofing of domes and vaults done without use of chemicals | Natural water-bodies that are self maintaining | All plants are indigenous requiring minimum watering | Waste water is treated and feeds fruit trees | Solar PV with battery, solar water heater, solar cooker for cooking

RESEARCH OBJECTIVES

1. Effectiveness of brick masonry hemispherical domes (internal dia 4.8 m) and segmental vaults (rise 0.55 m and 3 m span) to provide thermal comfort as per adaptive thermal comfort model of ASHRAE 55 across the year as a naturally ventilated building without using any electrical system such as fan to generate air velocity.
2. Identify the time lag in thermal transmission occurring through different walls and roof.
3. Efficiency of the wind extractors installed in a ventilated opening at the top of the dome.
4. Establish the WWR for hemispherical dome space and study it vis-à-vis its adequacy of sufficient air movement.

APPROACH

Within the CBERD (US-India Center for Building Energy Research and Development) project, under the umbrella of Auroville Center for Scientific Research (AV CSR) we are monitoring this building since September 2013 with hourly readings from 10 loggers and 15 sensors placed within the two domes on the first floor and the space on the ground floor formed by exposed brick vaults. The domes have a slightly different construction type: one is with squinches on a square base and another is with precast concrete circular beams also on a square base from where the dome springs. The two domes also have different ventilation system for hot air evacuation (Ref Fig 5 & 6).

Mona Doctor-Pingel has an independent architectural practice, Studio Naqshbandi, and is a team member of CBERD project. Rajan Rawal is Director, Center for Advanced Research in Building Science and Energy, CEPT University. Anna Bakhlina, is an architect, Studio Naqshbandi. Vijai Krishnaraj is an instrumentation engineer, CSR, Philippe Bourdon is a student in construction and energy engineering, ESIROI, Reunion Island

Logic of loggers placement

Surface temperature sensors are placed inside and outside the dome surfaces (at different heights) within the dome. Each of the sensors is covered with a white thermocol strip (25 mm x 50 mm x 5mm, Figure 7.5) to protect the sensor and to enable easy adhesion to the surface. One free hanging logger is placed inside each dome and the vault to measure air temperature and RH in the rooms (approximately 1.50 m above the ground, on the height relative to occupants use). There is a logger installed in a thermocol box (adaptation of the Stevenson screen) outside the residence for ambient temperature measurements. (For the type of loggers used and location refer the table and illustration – Fig. 2, 3, 4).

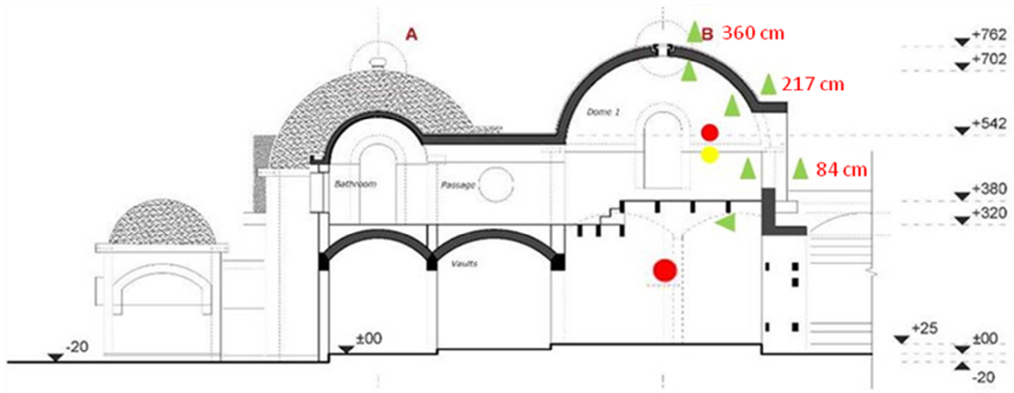


Figure 2 Section A-A' through **Dome 1** with placed data loggers and surf temp sensors placement (color code Figure 4)

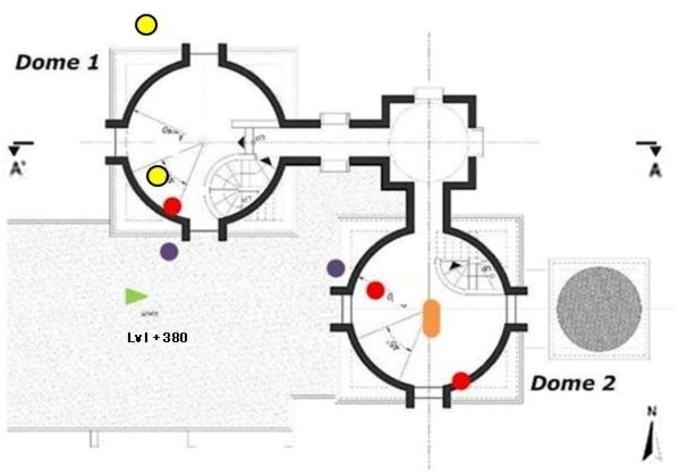


Figure 3 First floor plan with loggers placement.

	ONSET loggers			
	logger type	measurments	№ of loggers	accuracy :
	U12-012	temp, RH,Lux	2	T : ±0.35° C From (0 to 50 ° C) RH: ± 2.5% (from 10 to 90 %)
	U12-013	temp, RH,	4	T : ±0.35° C From (0 to 50 ° C) RH : ± 2.5% (from 10 to 90 %) External Input Channels : ± 2 mV ± 2.5% of absolute reading
	U12-006	-	2	± 2 mV ± 2.5% of absolute reading ± 2 mV ± 1% of reading for logger-powered sensors
	UX100-011	temp, RH,	2	T : ±0.21°C from 0° to 50°C RH : ±2.5% from 10% to 90% typical to a maximum of ±3.5% including hysteresis
	ONSET sensors			
	TMC6-HE 6' (6 ft) TMC20-HD (20 ft)	surf temp (thermistors)	14	±0.25°C from 0° to 50°C
	T-DCI-F900-L-O	air-velocity (single drection,hotwire)	1	+/-0.05 m/s or 1% full-scale

Figure 4 List of loggers and sensors.

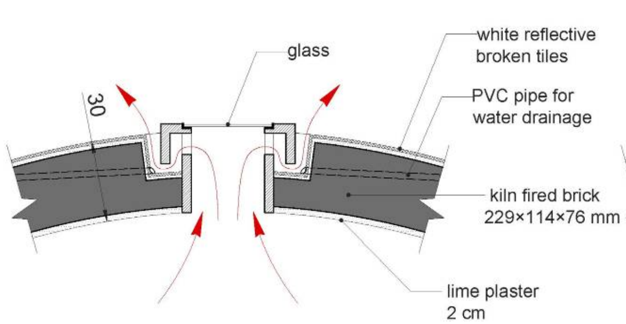


Figure 5 Detail B. Dome 1. Air vent.

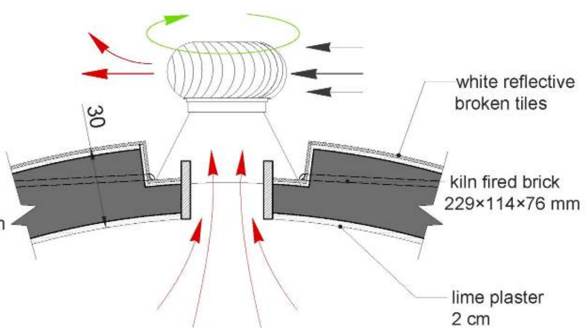


Figure 6 Detail A. Dome 2. Air vent with wind extractor.

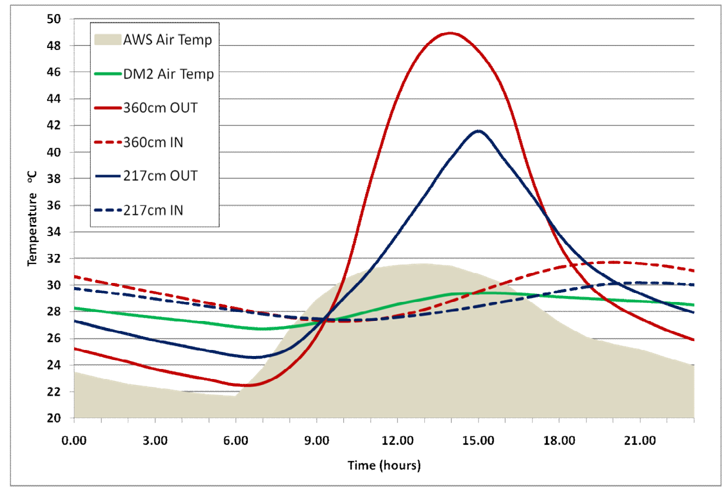
Additionally hand held readings are taken every three weeks, measuring air, globe and surface temperatures, air-velocity and humidity in every room under study as well as checking for any specifics that could not be taken by continual data logging. Any changes or abnormalities are recorded meticulously.

Surface temperature sensors are placed on ceiling and rooftop both for the vault and the domes. Weather data is obtained from an Automatic Weather Station (AWS) set up by the Indian space research organization at Auroville.

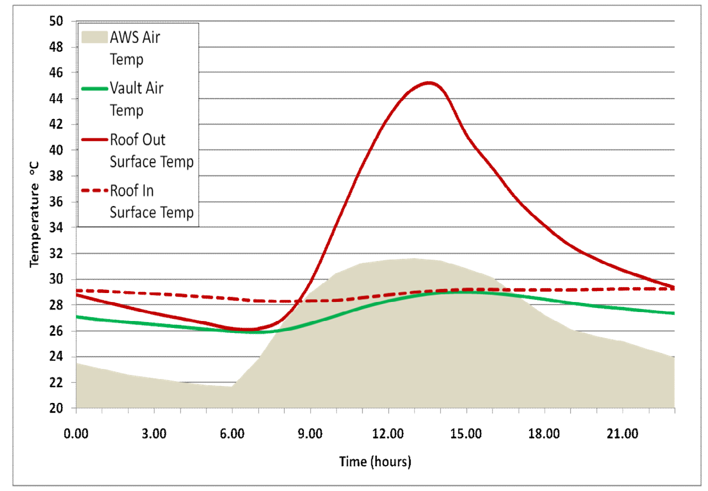
Figure 7 From the left: **1** - Dome with rotating arm under construction; **2** – Air vent opening detail on the top of the dome; **3** – Dome 2: Air vent with wind extractor; **4-** Air-velocity sensor fixed in the Dome 2; **5** – Fixed surface temp sensor on the vault covered with white thermocol strip

OUTCOMES

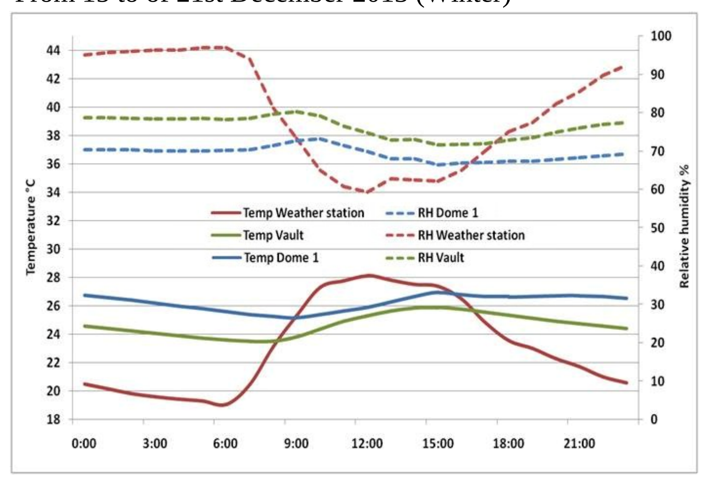
Graph 1. Hourly values of mean surface temperature for Dome 2 - IN vs. OUT March 2014



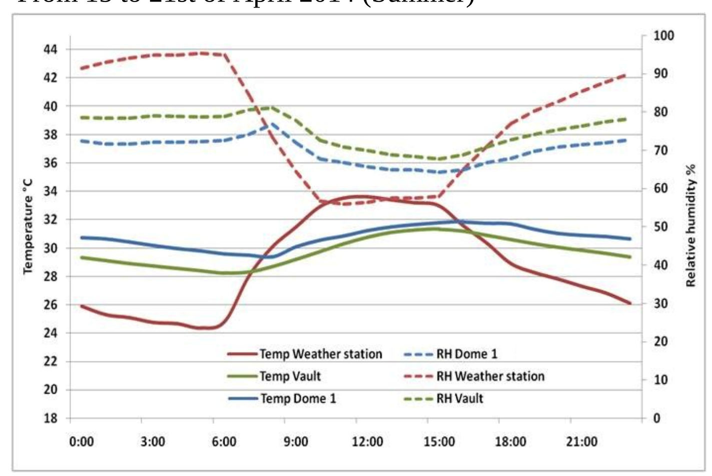
Graph 2. Hourly values of mean surface Temperature for Vault - IN vs. OUT March 2014



Graph 3. Hourly values of mean Relative Humidity and Ambient Temperature of Dome 1 vs. Vault From 15 to of 21st December 2013 (Winter)



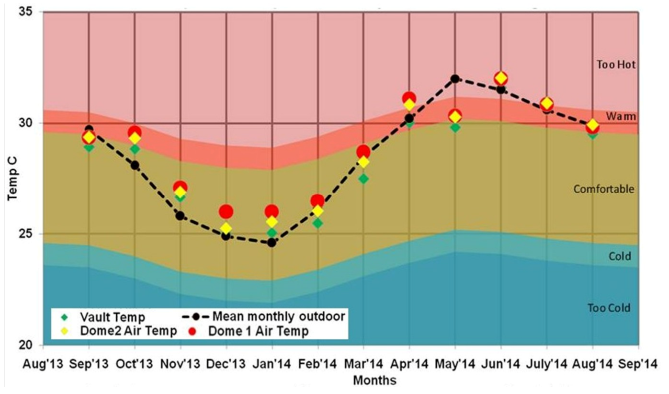
Graph 4. Hourly values of mean Relative Humidity and Ambient Temperature of Dome 1 vs. Vault From 15 to 21st of April 2014 (Summer)



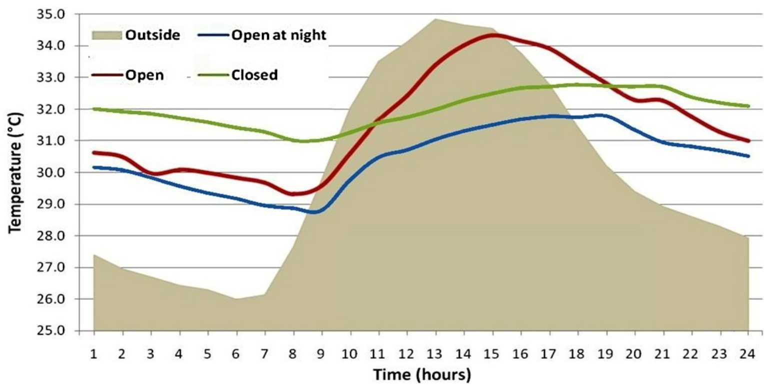
Graph 1 indicates that the outside surface temperatures are increasing towards the top of the dome, due to the increasing sun exposure, the same trend is reported for the inner surface with a 6 hours thermal lag (from outer to inner surface).
Graph 2 shows the performance of the vault in the same condition and through the same period of time as Graph 1. The time lag is more significant than the dome. The ceiling thermal lag is 8 hours from outer to inner surface. Ceiling surface temperature remains relatively stable thanks to high thermal mass and cross ventilation occurring in the vault.

Graph 3 and Graph 4 shows the comparison of the indoor air between the dome and vault looking at one week data in December (winter) and April (summer). In summer, the air temperature time lag is 3 hours for the vault and 4 hours for the dome. In winter, time lags dropped to 2 and 3 hours. Winter sees lower time lags but the same trend remains, the vault has the shortest air time lag which is synonymous to a more efficient cross ventilation.

Graph 5. Values of mean temperature in Dome 1, Dome 2 and Vault from Sep 2013 till Aug 2014 with Adaptive comfort zones (CARBSE), for Naturally Ventilated Buildings, *(13^{0}N, Chennai)*



Graph 6. Dome 1 air temperature with 3 different opening scenarios (weekly mean in April-May 2014): Windows closed throughout day & night; Windows open throughout day & night; Windows open at night and closed during the day



Graph 5: Overlapping the mean monthly temperatures of the building with the adaptive thermal comfort zones elaborated by CARBSE for Chennai, we can observe that the vault remains within the comfort range from September to May, whereas domes are within the comfort range from September to April (without any electrical ventilation system). Dome 2 is slightly cooler than the Dome 1, the major difference coming from the wind extractor proving that wind extractor helps to reduce the indoor temperature by increasing hot air extraction even when windows are closed. We can conclude that vaulted space shows better thermal performance.
Graph 6 compares the air temperature for three windows opening scenarios in Dome 1 and clearly indicates that the strategy to close the windows during the day to keep the fresh air and opening at night to cool down shows the best results. Detailed analysis of our data shows that windows open at day (09-18hrs) increases the indoor air temperature by 2°C more than when they are closed. Also windows open at night (18-09 hrs) allows an extra cooling of 1.2 °C than when they are closed.

Air Velocity measurement in Dome 2: The maximum and minimum air velocity recorded at the wind extractor is 1.54 m/s and 0.11 m/s respectively. The average is 0.57 m/s. The hourly mean values show that the air velocity increases at night time when land breeze prevails. More data and studies need to be undertaken with sophisticated instruments on the air movement in the room especially for the cross ventilation.

Surface to Volume Ratio and WWR study.
The vault has large overhangs on the south and north (1.2 m) and walls that are shaded / shared on the east and west. The domes have smaller overhangs on openings only (0.6 m) and the dome surface gets heated by direct sun radiation throughout the day, while the vault get alternately heated on the East then on the West side, not both at the same time. This difference has a repercussion on heat transmission and storage in the walls.

Table 1. Surface, volume and WWR calculation of the room with spherical dome and comparison with an equivalent vault-flat roof room interims of area & volume.

	Existing Dome	Equivalent Vault
Floor surface area	23 m^2	23 m^2
Internal volume	60.2 m^2	60.2 m^2
Internal height	3.6 m	2.61 m
Exterior surface area	79.5 m^2	88.8 m^2
Exterior wall surface area *	69.56 m^2	60.71 m^2
Surface area of openings	6.71 m^2	32 m^2
Window to Wall Ratio	**9.6%**	**36%**

* Exterior semi-spherical dome surface is counted as a wall surface

Comparing the WWR for vault and dome shows that the total area of opening is much less in the dome, mainly due to structural constraints. For the warm humid zone this leads to less possibility for ventilation and air movement.

CONCLUSIONS

- Thermal comfort can be achieved in a naturally ventilated building under a warm and humid climate using passive strategies. The overall performance of vault is more satisfactory than the dome in this case study due to its larger openings enhancing cross ventilation and lesser solar heat transmission.
- The thermal mass of the domes and vaults ensures a time lag of 2 - 4 hours for the air temperature. Domes' being less than the vault.
- Temperature on the surface of the dome increases towards the top.
- Ventilation at the center of the dome is important. The installation of the aluminum wind extractor on the top of the dome fares better than the air vent design as it increase hot air dissipation.
- The dome and vault are more comfortable in the winter than in summer months in warm humid climate. Other factors such as lifestyle habits and indoor air velocity would need to be considered.
- Air-velocity data for all the areas under study was not available. This would be important to take into account for naturally ventilated areas, especially without electrical ventilation systems.
- A comparison with modern RCC dwellings in the same climate can be undertaken in the next phase of research.
- Occupied buildings that are naturally ventilated are difficult to monitor, since behavior patterns and use of the building change with the outdoor conditions.

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