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Thermal performance of non air-conditioned buildings with vaulted roofs in comparison with flat roofs

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Abstract

Vaulted or domed roofs have been frequently adopted by builders and architects throughout the Middle East and other hot dry areas. However, the thermal performance of such buildings under hot dry climatic conditions has rarely been quantitatively studied. In this paper, a detailed finite element model for the investigation of the thermal performance of non air-conditioned buildings with vaulted roofs (VR) is suggested based on two-dimensional unsteady heat transfer in such roofs and solar geometry. This model allows a comparison of the thermal performance of non air-conditioned buildings with a VR and a flat roof (FR) under different climatic conditions. Results obtained by numerical calculation show that, irrespective of building type the VRs are applied to, buildings with a VR have lower indoor temperatures as compared to those with a FR. The reason is that such roofs dissipate more heat than a FR does by convection and thermal radiation at night due to the enlarged curved surfaces. This implies that such roof forms are suitable for buildings located in hot dry regions but not for those located in hot humid areas, and reasonably explains why curved roofs have been extensively adopted by builders and architects in the hot dry areas in the past. However, with the decrease in the half rim angle of a VR, the difference of indoor thermal condition between a VR and a FR building becomes small and insignificant. Results also indicate that the indoor air temperature is slightly influenced by the half rim angle θ_0 and the orientation ϕ_v of the VR. To be effective to create a favorable thermal condition inside buildings with a VR under hot dry climatic conditions, the half rim angle of a VR should be $\theta_0 > 50^\circ$, instead of $\theta_0 < 50^\circ$, which is the optimal half rim angle of a VR of air-conditioned buildings, as found by the present authors in a previous study.

Keywords: Vaulted roof; Thermal performance; Non air-conditioned buildings

1. Introduction

Domed and vaulted roofs (VRs) had been extensively used in traditional and vernacular buildings in hot dry regions. Such roofs were commonly constructed using stone or brick masonry with a plaster finish. Usually a small opening close to the top of the gable walls of vaults provides ventilation and exhausts hot air from the upper strata. Various explanations have been given for the frequent appearance of both roof types. One common point of view is that the material of their construction, stone, was abundant in arid zones and the construction of such roof shapes was possible without using wood. Climate-related explanations given for curved roofs have been investigated by many researchers. Some researchers have assumed that these roofs were adopted out of climatic and environmental considerations, while others stressed religious and cultural issues of geometry. Common among these explanations was the assumption that, in hot dry climates, buildings with curved roofs maintained lower indoor temperatures during the hot summer months [1]

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Nomenclature

A	area (m^2)
C_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
d	thickness of roof (m)
h	convective heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L	length of roof base (m)
m_{ach}	air change rate ($kg\,s^{-1}$)
Q	daily heat flow through roof or daily heat gain of roofs ($J\,m^{-2}$)
q	heat flux through roof base or net heat gain of roofs ($W\,m^{-2}$)
R	internal radius of a VR (m)
r	radial coordinate (m)
Rh	relative humidity of air (%)
S	solar heat gain of roof ($W\,m^{-2}$)
T	temperature (°C)
U	heat loss coefficient due to conduction ($W\,K^{-1}\,m^{-2}$)
W	width of roof base (m)
t	time (s)
x	coordinate from the external surface of a FR
z	depth of ground layers under the floor
α	absorptance
ε	emittance
ϕ_v	orientation of vaults, measured from due south to west (deg.)
μ	thermal diffusivity ($m^2\,s^{-1}$)
θ	polar angle from the zenith (deg.)
θ_0	half rim angle of a VR (deg.)
ρ	density of roof ($kg\,m^{-3}$)
ρ_g	reflectance of ground
σ	Stefan–Boltzmann constant ($W\,m^2\,K^4$)

Subscripts

a	ambient air
b	roof base
dp	dew point
ex	external surface
f	flat roof, floor
g	net heat gain of roofs
i	indoor air
in	internal surface
n	normal
r	roof
s	soil, solar ray
sky	sky
v	vaulted roof
w	wall

and reflected more radiation than flat roofs (FRs) [2–5]. The reason for this assumption was mainly qualitative, based on the assessed interaction between desert climate and the enlarged curved roof surface as compared to FRs. Olgyay [6] and Fathy [7] suggested that an advantage of curved roofs was that they reduced local radiant flux on a rounded surface and therefore resulted in lower surface temperatures, so the heat flowing into buildings through curved roofs was also reduced. Another explanation given for the abundance of curved roofs in hot arid regions was that these absorb the same amount of radiation as compared with FRs, but dissipate more heat by convection. Due to thermal stratification, the air heated within a building with a curved roof gathers in the space under the roof, thus creating more comfortable conditions on the living/floor level [3,8]. Nevertheless, contemporary architecture adopted such roof forms without questioning the "common knowledge" regarding their thermal behavior.

Pearlmutter [9] made a first attempt to quantitatively compare the thermal behavior of vaulted and FRs in terms of indoor temperatures. Two pairs of test cells were constructed, each of the pairs consisting of one cell with a FR and one with a semi-cylindrical roof. The roofs of one pair were painted black matte, and those of another pair were painted white. Roofs were made of 1 mm thick galvanized sheet metal, and the walls and floors were constructed of plywood with 5 cm expanded polystyrene insulation. Each structure measured 50 cm × 50 cm in plan, and 50 cm in height from the floor to the base of roof. Pearlmutter found that no significant difference between the thermal condition of the south (S)—north (N) facing VRs and the east (E)—west (W) facing ones (the central axial line of the vault oriented parallel to the S–N direction for an E–W facing VR); thermal stratification under VRs was found to be higher than that under flat ones; vaults maintained lower internal temperatures than their flat counterparts throughout most of the daytime hours, especially for the pair with roofs painted black.

Theoretical calculations of solar gains absorbed by VRs compared with FRs were also done based on solar geometry. However, a sensitivity analysis of solar heat gains of VRs to their structural parameters was not performed. Such work was recently undertaken by Tang et al. [10] based on solar geometry and the angular-dependent solar absorptance of roof surfaces. This research showed that a domed roof with half rim angle of 90° absorbs 20% more beam radiation, 50% more sky diffuse radiation, and 30% more total radiation (not including ground reflected radiation) than that received by a FR. It also showed that a S–N facing VR with half rim angle of 90° absorbs almost the same amount of beam radiation, 28.5% more sky diffuse radiation, and