Energy and Buildings 35 (2003) 539–548

ENERGY and BUILDINGS

www.elsevier.com/locate/enbuild

An analysis of absorbed radiation by domed and vaulted roofs as compared with flat roofs

Tang Runsheng*, I.A. Meir, Y. Etzion

The Desert Architecture Unit, J. Blaustein Institute for Desert Studies, Ben-Gurion University of the Negev, Sede Boqer Campus, 84990, Israel

Received 1 March 2002; received in revised form 20 July 2002; accepted 1 August 2002

Abstract

Domed or vaulted roofs have been extensively used in buildings throughout the Middle East and other hot arid regions. Many studies have focused on climate-related considerations, but very little quantitative research exists in the literature. In this study, an attempt was made to calculate the insolation absorbed by these roofs, as compared with flat roofs, based on angular dependence of absorptance and solar geometry. Results showed that a domed or vaulted roof will absorb more solar radiation than its corresponding flat roof. The ratios K_b, K_{tot} increase with the increase of the half dome or vault angle but are insignificantly affected by climate characteristics and latitude of the location. It was also seen that a south–north facing vaulted roof both reduces the solar heat gain of buildings in summer months and increases solar heat gain in winter months compared to one which faces east–west; the greater the proportion of area exposed to the sun is, the smaller the amount of beam radiation that will be absorbed by a curved roof. Furthermore, results showed that even if absorptance is assumed to be constant this would affect total solar heat gain of the roofs studied by less than 4%.

Keywords: Angular dependence of absorptance; Absorbed radiation; Half dome or vault angle

1. Introduction

Domed and vaulted roofs are common in buildings in the Middle East and other hot arid regions. These buildings are mostly built with stone or brick masonry with a plaster finish. 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 such roof shapes were possible without using wood. Some researchers assumed that these roof forms were adopted out of environmental, religious and cultural considerations. Common among these interpretations was the belief that buildings with curved roofs in hot dry climate maintained lower temperatures during the hot summer months and reflected more radiation than flat roofs [1–3].

Several specific factors have been suggested to support this assumption, each of which was based on some aspect of the desert climate and its relationship to roof form. However, these descriptions of the thermal performance of curved roofs in vernacular buildings were qualitative in nature rather than relying on measured and calculated data. Olgyay [4] suggested that an advantage of curved roofs was that it diluted intensive radiation on a rounded surface and therefore resulted in lower surface temperatures. A similar explanation was based on the assumption that the intensity of solar radiation was spread over a larger area and the average solar heat gains of the roof and heat transmission to the interior of buildings were reduced [5]. Another explanation given for curved roofs was that these absorb the same amount of radiation but dissipate more heat by convection as compared with flat roof, whereas due to thermal stratification the hot air inside the building accumulates under the curved roof over the living area of room, thus, creating more comfortable conditions [6]. Pearlmutter [7] analyzed the solar radiation gain by vaulted roofs using solar geometry and compared their thermal behavior with flat roofs by measuring the temperature inside test buildings with roofs made of 1 mm thick galvanized metal sheet and walls made of plywood. Each one of the test buildings measured 50 cm × 50 cm in plan, and 50 cm in height from the floor to the base of the roof. It was shown that the vaulted roof had greater thermal stability and potentially favorable daytime temperatures, whereas no significant differences in thermal behavior existed between north–south and east–west facing roofs. However, the angular dependence of absorptance of a surface had been neglected in his mathematical analysis. The objective of this study was to

* Corresponding author.
E-mail address: runsheng@bgumail.bgu.ac.il (T. Runsheng).

0378-7788/02/$ – see front matter
PII: S0378-7788(02)00165-2

calculate the solar heat gains of domed or vaulted roofs based on solar geometry and angular dependence of absorptance of a surface, by comparing absorbed insolation by domed or vaulted roofs to that by their corresponding flat roof; calculate the effects of the geometric parameter of half dome or vault angle on solar heat gains; and suggest some recommendations for their constructions in order to improve their performance in hot arid climate with intensive radiation during the summer months.

2. Angular dependence of solar absorptance

The solar absorptance of a surface depends on the incidence angle of solar rays and the properties of the surface [8]. Solar absorptance decreases with the increase of incidence angle, as shown in Fig. 1. However, very little information was available about its angular dependence. Here, as an example, a correlation recommended by Duffie and Beckman [8] was adopted as follows:

$$\frac{\alpha}{\alpha_n} = 1 + 2.0345 \times 10^{-3}\,\theta - 1.99 \times 10^{-4}\,\theta^2 + 5.324 \times 10^{-6}\,\theta^3 - 4.799 \times 10^{-8}\,\theta^4 \quad (0 \le \theta \le 80) \tag{1}$$

$$\frac{\alpha}{\alpha_n} = 0.064938(90 - \theta) \quad (\text{as } 80 < \theta < 90) \tag{1a}$$

where α_n is the absorptance when the solar rays strike vertically at a surface. For diffuse radiation, assuming its distribution is isotropic over the hemisphere above a surface, the equivalent average absorptance $\langle a \rangle$ may be calculated by calculating the weighted average absorptance over the whole hemisphere as follows:

$$\langle a \rangle = \int_0^{90} 2 \times \sin\theta \times \cos\theta \times \alpha(\theta)\,\mathrm{d}\theta \tag{2}$$

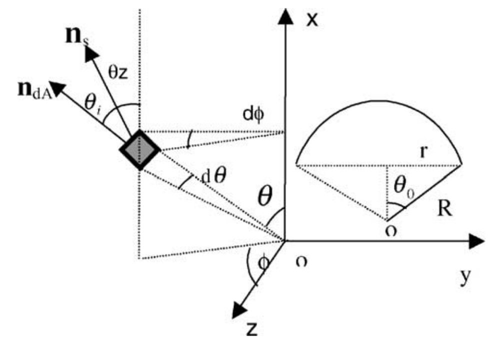

Fig. 2. Illustration of solar rays vector $\boldsymbol{n}_s$, normal vector $\boldsymbol{n}_{dA}$ of dA at any point of a domed roof.

Substituting Eq. (1) into Eq. (2) and using numerical integration, we have

$$\langle a \rangle = 0.93335 \times a_n \tag{3}$$

2.1. Absorbed beam radiation by domed roofs

In order to simplify the analysis, we suggest such a coordinate system that its origin is located at the center of the sphere of a domed roof with radius R and half dome angle θ_0($\sin\theta_0 = r/R$, r being the radius of the base of the domed roof). Beam radiation I_b strikes at dA of the domed roof at a zenithal angle θ_z, shown in Fig. 2, assuming the solar rays are coplanar with plane XOZ (it is reasonable due to symmetric spherical domed roof). Thus, at any given time, the beam radiation absorbed by area dA of the domed roof is expressed by the following equation:

$$\mathrm{d}I_{b,\mathrm{dome}} = I_b \times \mathrm{d}A \times \cos(\theta_i) \times \alpha(\theta_i) = I_b R^2 \alpha_n \sin(\theta)\,\mathrm{d}\theta\,\mathrm{d}\phi\, f(\theta_i)\cos(\theta_i) \tag{4}$$

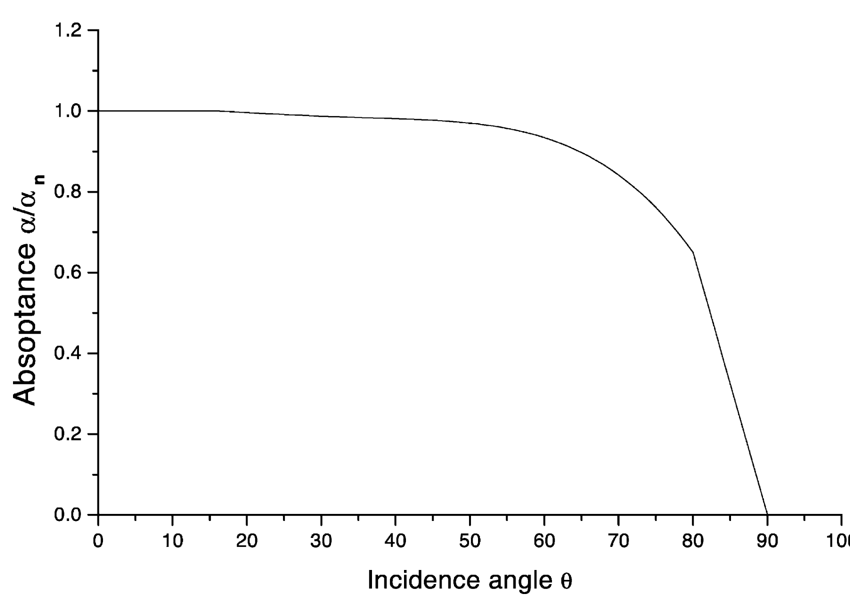

Fig. 1. Dependence of absorptance on incidence angle.