Available online at www.sciencedirect.com
ScienceDirect
Energy and Buildings 40 (2008) 265–275
ENERGY and BUILDINGS
www.elsevier.com/locate/enbuild

Thermal analysis of vaulted roofs

M. Hadavand, M. Yaghoubi [1,*], H. Emdad

Mechanical Engineering Department, Engineering School, Shiraz University, Fars74348-51154 Shiraz, Iran

Received 19 December 2006; received in revised form 3 February 2007; accepted 16 February 2007

Abstract

In hot arid regions, cooling buildings by passive techniques is very important regarding energy saving and the need to keep clean the environment. In such areas, domed and vaulted roofs are widely used for centuries, such as in the Middle East region and central part of Iran. In this article analysis is made to explore east–west direction of wind flow around north–south vaulted roofs and flat roof buildings. Combined convection and solar radiation over the roofs is considered to studying thermal performances of vaulted roofs and comparing their heat transfer with flat roofs. Two-dimensional RNG k–ε turbulence model is incorporated to predict turbulent flow field as well as separation and recirculating patterns around the vaulted roofs and flat roof buildings. Solar radiation distribution over the roofs is determined based on an appropriate model applicable to hot arid regions of Iran. Pressure differences above the vaulted roof are compared with flat roof for various rim angles and different wind speeds. Heat transfer to the building with respect to time is determined for a certain inside ceiling design temperature, various wind flows and vault shapes, and results are compared with corresponding flat roof. It was found that daily average heat flux for all vaulted roofs, except vaulted roof of rim angle 180° is less than flat roof and it reduces further by increasing wind speed.

Keywords: RNG k–ε turbulence model; Solar radiation; Flat roof; Air-conditioning; Passive cooling

1. Introduction

Natural ventilation and passive cooling have been traditionally two important features in old Persian architectures [1]. Domed and vaulted roofs had been extensively used in traditional and vernacular buildings in hot dry regions [2]. These structures of buildings are mainly located in desert communities in near and Middle East areas and for Iran they are mostly located in south, center and eastern regions. Vault and dome roof buildings are mostly built with brick masonry [3,4]. The use of adobe or mud bricks as the basic construction material in the rural areas of Iran is perhaps as old as the Persian civilization itself. Lack of other materials such as timber, etc., was the primary reason for the selection of adobe structures. But, their low costs and good thermal performance must have been the main reasons for their popularity [5]. These kinds of roofs have been extensively used in order to protect against wind storm and strong sunshine and its consequent of lower heat transfer into the building [6]. Bahadori [7] in 1978 has introduced the role of domed roofs in ventilation and saving cool water in cistern for hot seasons through wind flow around these kinds of roof buildings and wind catchers (Baudgir) in hot arid regions of Iran. Natural ventilation and evaporative cooling of water have been the main elements to keep cool water in the cistern in hot summer days. He reported that 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. Wind flow and pressure effect on building with flat roofs have been studied extensively [8,9]. A detail review of wind load for flat roof buildings has been presented by Statbopoulos [9]. Experimental studies of air flow field has been carried by Yaghoubi [1] for simple models of vaulted roofs buildings in a two-dimensional low speed wind tunnel for low velocity smoke flows. Later, Sabzevari and Yaghoubi [6] tested some flow visualization on a composition of models of isolated cuboids, cuboid with domed roof and multiple domed roof buildings subjected to a light boundary layer wind in a wind tunnel and identified various flow patterns. Pearlmutter [10] quantitatively compared thermal behavior of vaulted and flat roofs in terms of indoor temperatures. He found that no significant difference between the thermal condition of the south–north facing vaulted roofs and the east–west facing ones; thermal stratification under

* Corresponding author. Tel.: +98 711 2301672; fax: +98 711 6272060.
E-mail address: yaghoub@shirazu.ac.ir (M. Yaghoubi).
[1] Member, Academy of Sciences, I.R. Iran.

0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2007.02.024

Nomenclature

A_1, A_2, A_3	constant parameter in Daneshyar model
C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$	constant coefficient in turbulence model
C_P	specific heat
CF	cloud factor
F_{wg}	shape factor of roof surface and ground
F_{ws}	shape factor of roof and sky
G_{beam}	solar beam radiation
G_{diff}	diffuse radiation
G_t	total energy which receive on an horizontal surface
h	convective heat transfer coefficient
H	height of building
k	turbulent kinetic energy
$\overline{Nu}$	mean Nusselt number $\overline{Nu} = \bar{h}H/\lambda$
P	pressure
Pr	Prandtl number
Pr_t	turbulent Prandtl number
q	heat flux
Re	Reynolds number $Re = \rho\mu_\infty H/\mu$
S_{ij}	mean strain rate transform
T	temperature
t	time
u_i	index notation of velocity components
x_1, x_2	stream wise and cross-stream coordinates
X_r	reattachment length

Greek letters

α_k, α_ε	constant coefficient in turbulence model
α	absorptance
α_s	solar altitude angle
β_o	slop angle
ε	turbulent dissipation rate
ε	emittance
η, η_o	parameters in RNG k–ε model
κ	Von Karman's constant
λ	thermal conductivity
μ, μ_t	laminar and turbulent viscosity
θ	polar angle of vaulted roof from the forward wall
θ_0	vaulted roof rim angle
ρ	fluid density
ρ_g	ground reflectance
σ	Stefan–Boltzmann constant
ψ	the angle of separation point

Subscripts

∞	uniform free stream condition
a	ambient air
f	flat roof
in	indoor condition
r	roof
s	solar
sky	sky
sur	surface
v	vaulted roof

vaulted roofs 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. Bahadori and Haghighat [5] estimated inside air and the mean radiant temperatures of two kinds of buildings, flat roof and domed roof through a thermal network analysis. The analysis was repeated for both buildings when their ceilings and inside wall surfaces were kept moist and evaporately cooled. It is shown that with adequate natural ventilation, the temperature of the moist surfaces is reduced appreciably and the floor surface temperature and the air temperatures are also reduced and comfortable condition were provided for the dwellers. According to their studies, domed roofs with holes in their crowns can increase natural ventilation which enhances evaporation from wet surfaces. Gomez-Munoz et al. [11] calculated solar energy which is absorbed by hemispherical domed roofs and flat roofs in Mexico. They demonstrated that the hemispherical vault receives around 35% less energy than the flat roofs for the specified conditions. The amount of incidence solar energy was reported in terms of energy per unit area, and regarding the exposed surface of the dome which has larger surface than flat roofs, hence, total energy received will be different. Tang et al. [3] have studied solar heat gained by domed, vaulted and flat surfaces. They have shown that a south–north facing vaulted roof with rim angle of 180° (Fig. 1) absorbs almost the same amount of beam radiation, 28.5% more sky diffuse radiation, and 10% more total radiation (not including ground reflected radiation) than that received by a flat roof. The same study showed that the ratio of radiation absorbed by curved roofs to that absorbed by flat ones increases with enlarging rim angle. Tang et al. [4] have also made another attempt to calculate heat flux and daily heat flow through curved roofs into an air-conditioned building based on three dimensional unsteady heat transfer equations. They have found that the daily cooling load for a south–north oriented vault of $\theta_0 = 180°$ is about 20% higher than a flat roof. They have assumed a constant heat transfer coefficient for all the elements of mesh on various roofs which is questionable. Tang et al. [12] in their recent studies have shown that a non-air conditioned building with a vaulted roof, irrespective of building's type, has lower indoor air temperature as compared to those with a flat roof during the daytime under a typical hot dry climate condition. They reported that to create a favorable thermal condition inside a non air-conditioning building under hot dry

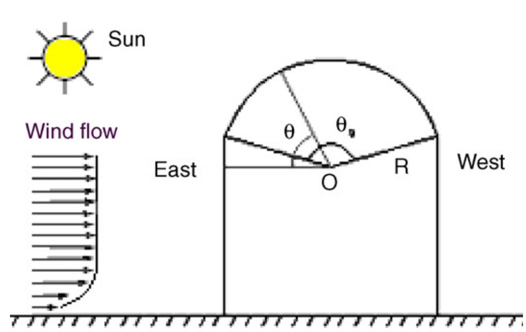

Fig. 1. A vaulted roof building with sun rotation.