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A study of vaulted roof assisted evaporative cooling channel for natural cooling of 1-floor buildings

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ABSTRACT

The application of evaporative cooling technique in a 1-floor stand-alone house with vaulted roof, in order to meet the required thermal needs of inhabitants and natural cooling of the interior space, has been studied in this paper. In order to investigate the capability of the system to meet thermal comfort conditions in different environmental conditions, the performance of the system has been numerically investigated for wide ranges of wind velocities, ambient air temperatures and relative humidity values. The results indicate that when the wind velocity is higher than 0.4 m/s, the air inside the building will be ventilated efficiently. In addition, as the wind velocity or the ambient air temperature increases, thermal comfort is achieved at lower values of relative humidity. The maximum allowable values for relative humidity of the ambient air to meet thermal comfort conditions are calculated based on the adaptive thermal comfort standards, and the application of the proposed system in stand-alone buildings for the centers of the provinces of Iran is investigated.

1. Introduction

Nowadays, the application of mechanical air conditioning systems in buildings is becoming more and more popular, especially in the residential ones; But this kind of devices consume a great deal of energy. In hot summer regions, reaching thermal comfort conditions by the use of such devices is neither economic nor efficient. Surely, if the advantages and the disadvantages of these appliances are investigated well, no one would recommend them.

Good alternatives for the mechanical air conditioning devices are natural air conditioning systems. Such systems have been used since long times ago, including wind catchers (baudgirs) in Iran, Saudi Arabia, Egypt, Pakistan and also in houses with domed roofs in the hot desert regions of Iran. Much research has been carried out on the use of vaulted roofs too; For instance, Runsheng, Meir, and Etzion (2003) studied the insolation absorbed by vaulted and domed roofs, as compared with flat roofs based on angular dependence of absorbance and solar geometry. The results showed that vaulted and domed roofs absorb more solar radiation than its corresponding flat roofs. Moreover, a south-north facing vaulted roof reduces both 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. Gómez-Muñoz, Porta-Gándara, and Heard (2003) studied the solar and energy performance of a hemispherical vault roof, including the auto-shading instant effect during several days for different latitudes and throughout the year. They compared the results with the standard horizontal flat roofing used in the typical modern low-cost housing in Mexico. It was found that the hemispherical vault receives around 35% less energy than the flat roof between the equinoxes, besides having other advantages such as a greater ceiling height, natural ventilation and illumination possibilities, and structural stability. Runsheng, Meir, and Wu (2006) investigated the thermal performance of buildings with vaulted or domed roofs under hot dry climatic conditions quantitatively. They suggested a finite element model based on two-dimensional unsteady heat transfer in such roofs and solar geometry for the investigation of the thermal performance of non air-conditioned buildings with vaulted roofs. Results showed that irrespective of building type the vaulted roofs are applied to, buildings with a vaulted roof have lower indoor temperatures as compared to those with a flat roof. In addition, such roofs are suitable for buildings located in hot dry regions but not for those located in hot humid areas. However, with the decrease in the half rim angle of a vaulted roof, the difference of indoor thermal condition between a vaulted roof and a flat roof building becomes small and insignificant.

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Nomenclature

A	area (m^2)
ACH	air change per hour (h^{-1})
b	width of the Cooling channel (m)
C_p	specific heat of air at constant pressure (J/kg K)
Cμ	empirical constants in the realizable k-e turbulence model
d	height of the computational domain
E	energy (J)
f	wettability (%)
f_i	external body force in jth direction (N/m^3)
g	gravitational acceleration (m/s^2)
h	convection heat transfer coefficient (W/m^2K)
h_m	mass transfer coefficient (kg/sm^2)
H	enthalpy (kJ/kg)
J	flux of element penetration (kg/m^2s)
k	turbulent kinetic energy (m^2/s^2)
L	length (m)
m	air mass flow rate (kg/s)
P	pressure (Pa)
Q	heat flux (W/m^2)
Q_t	cooling demand of room (W)
RH	relative humidity (%)
S_h	volumetric energy source (J/m^3)
t	thickness (m)
T	temperature (K)
U	overall heat transfer coefficient (W/m^2K)
u	velocity (m/s)
$\overline{u}$	mean velocity of the fluid
u^*	dimensionless velocity
x,y	cartesian coordinate (m)
y^*	dimensionless wall coordinate
Y	mass fraction of species
Z	height of the inlet air vent (m)

Greek symbols

ε	turbulent dissipation rate (m^2/s^3)
λ	heat conduction coefficient (W/mK)
μ	dynamic viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
τ_w	wall shear stress (Pa)
ω	humidity ratio of air(kg_{water}/kg_{air})
φ	scalar property (k or ε)
Γ	diffusion coefficient

Dimensionless terms

Pr	Prandtl number ($C_f\mu_f/k_f$)
Pr_t	turbulent Prandtl number
Re	Reynolds number ($u_f d_{hyd}/\nu_f$)

Subscripts

a	ambient
cc	evaporative cooling channel
f	air flow
fg	latent heat
j,i	coordinate directions
ins	insulation
l	latent
out	Outlet of evaporative cooling channel
p	point near wall cell
pw	water vapor
r	room
v	vapor
w	water
wall	wall
wind	wind

Hadavand, Yaghoubi, and Emdad (2008) explored east-west direction of wind flow around north-south vaulted roofs and flat roof buildings. Combined convection and solar radiation over the roofs was considered to studying thermal performances of vaulted roofs and comparing their heat transfer with flat roofs. Two-dimensional RNG k-ε turbulence model was incorporated to predict turbulent flow field as well as separation and recirculating patterns around the vaulted roofs and flat roof buildings. Pressure differences above the vaulted roof were compared with flat roof for various rim angles and different wind speeds. 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. Asfour and Gadi (2008) investigated the potential of the vaulted roofs for improving wind-induced natural ventilation, by Fluent 5.5 software using a three-dimensional modeling. It was found that utilization of vaulted roofs for natural ventilation increases inflow rate of the building, and re-distribute internal airflow currents by attracting some of the air to leave through roof openings instead of walls openings. Natural ventilation performance of two equivalent domed and vaulted roofs was also compared. Results showed that there are many similarities between domed and vaulted roofs in terms of their natural ventilation performance, and the advantage of any roof shape in air suction is highly dependent on wind direction. Chel and Tiwari (2009) investigated thermal performance of an existing eco-friendly and low embodied energy vaulted roof passive house located at New Delhi. A thermal model of the house consisting of six interconnected rooms was developed based on energy balance equations which were solved by using fourth order Runge Kutta numerical method. The annual heating and cooling energy saving potential of the mud-house was determined as 1481 kWh/year and 1813 kWh/year respectively for New Delhi composite climate. The total mitigation of CO_2 emissions due to both heating and cooling energy saving potential was determined as 5.2 metric tons/year. Natalini, Morel, and Natalini (2013) presented the results of mean wind load coefficients on vaulted canopy roofs obtained in boundary layer tunnel tests, and the aerodynamics of vaulted canopy were discussed by taking into account the data produced during the last decade in South America.

A study of the previous researches shows that the application of the evaporative cooling technique in buildings with vaulted roofs has not been studied yet. Therefore, in this study, the capability of the evaporative cooling technique to achieve thermal comfort conditions and the dependency of the performance of such system on different environmental parameters (wind velocity, temperature degree and relative humidity of the ambient air) are investigated for a 1-floor building with vaulted roof. Since the air handling and cooling processes are totally natural, the adaptive thermal comfort criterion have been used in order to investigate the capability of this system to supply the cooling load which is needed for the building. It has to be mentioned that according to the adaptive thermal comfort standards (ATCS), the only important parameter to be satisfied is the proper temperature degree (Fig. 1) (Brager & de Dear, 2000). Accordingly, Indoor air velocity, relative humidity and asymmetric radiation haven't any effect on thermal comfort conditions and have not been considered here to evaluate thermal comfort conditions in the test room. It is because such systems do not