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Thermal study of a cistern's dome (the case of Motamed cistern in Lar, Iran)

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ABSTRACT

In this study thermal behavior of an active cistern is investigated experimentally and numerically for both wind and "no wind" conditions. The cistern is modeled using three-dimensional Finite Volume Method and quasi-steady state condition by considering variations of ambient temperature and intensity and direction of solar radiation. Temperature distributions on the outer surface of the dome and windcatchers are compared with thermography measurements for different hours of a day. Furthermore, natural ventilation caused by the heated dome is calculated by a two-dimensional quasi-steady modeling. The streamlines, velocity vectors, natural plume generated over the dome and temperature distributions are computed for different times during a day. The plume as well as the air motion inside the cistern is determined for different times during a typical day. Natural ventilation through the cistern opening and different wind-catchers are also calculated. Ventilation enhances convection heat transfer which is found non-uniform on the dome. Convection heat transfer coefficient changes between 2–10 W/m^2K and 12–37 W/m^2K for no-wind and wind-blowing conditions, respectively. The modeling shows that cisterns are appropriate system for storing cool water in hot arid regions.

1. Introduction

Cisterns are constructed for two purposes, first to store water in rainy months for use in dry months of the year and secondly to lower storage water temperature during the hot summer period. There are various types of cisterns, they may have a dome or flat roof; they may or may not have windcatchers and dome openings. The number or type of windcatchers can be different for any cistern. The most important part of a cistern is the roof, which prevents direct sunlight into the cistern. The most common types of roof in hot and arid climate regions of Iran are vault or dome roofs. These types of roofs are used in traditional buildings, mosques and cisterns. Utilizing domed roofs is a specific characteristic of cisterns, which are used for storing water.

Iranians were among the first people which to employ arched roofs in their buildings. The shortage of wood resources, especially long wood log, which were the main part of flat roofs, encouraged the architects to use arc roofs [1]. One of the most famous ancient arc roofs is the Taq Kasra at Ctesiphon (built 2000 B.C.) [2]. In the hot and arid regions of Iran, buildings are made of clay bricks covered with thatch, and this kind of masonry was one of the main elements for construction of homes [3]. In addition to the domes and the mentioned materials, windcatchers and shovadans (Iranian traditional underground rooms) are the other symbols of hot and dry climate in Iranian architecture which are used because of their good performance for creating favorable thermal comfort in hot summer condition [4].

Domes can emit and transfer more energy to the sky than flat roofs; owing to the larger area of domes [5]. Moreover, acceleration of air flow over the dome roofs increases convective heat transfer compared to flat roofs. They can enhance natural ventilation and cooling, which had been investigated by Yaghoubi [6] and Tavakol et al. [7]. Sabzevari and Yaghoubi [8] found that daily average heat flux to the indoor is less for arc roofs than flat roofs. Additionally, Hadavand et al. [9] noticed that the heat flux is reduced even further by increasing wind speed.

In addition to the effect of wind speed which has been surveyed in the previous studies, the influence of some physical parameters in reducing maximum indoor air temperature has been determined by Faghih and Bahadori [10]. Some of the parameters include airflow around the dome, solar radiation and thermal radiation heat

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Nomenclature

A	altitude
a, b	solid angles
$a_0{}^*$, $a_1{}^*$, k^*	constant parameter in the Hottel model
A_c	exposed surface area
C_P	specific heat
C_μ, $C_{1\varepsilon}$, $C_{2\varepsilon}$	constant coefficient in turbulence model
F_1', F_2'	new brightness coefficients
F_B	body force
h	convective heat transfer coefficient
h	height from the ground
I_0	solar constant
I_{beam}	beam radiation
I_{diff}	diffuse radiation
I_{ref}	radiation reflected by the ground
k	turbulent kinetic energy
k	thermal conductivity
n	day number
P	pressure
q	heat flux
r_d	solar radiation ratio
S_{ij}	distortion rate tensor
T	temperature
t	time
u	x-direction velocity components
V	velocity vector

Greek letters

ε	turbulent dissipation rate
$\alpha(\theta_i)$	absorbance coefficient
α_k, α_ε	constant coefficient in turbulence model
α_n	absorbance to normal surface
β	slop angle
γ	surface azimuth angle
δ	declination angle
ΔV	volume
θ	angel of incidence
θ_z	zenith angle
μ, μ_t	laminar and turbulent viscosity
ρ	density
ρ_g	ground reflectance
σ	Stefan–Boltzmann constant
τ_b	beam radiation transmittance
φ	latitude angle
ω	hour angle

Subscripts

a	ambient air
$cond$	conduction
$conv$	convection
ref	reference
s	solar
sky	sky
sur	surface
tot	total
w	wall

transfer exchange with the sky and ground. They considered that thermal performance could be improved by using a doomed roof instead of flat roofs and openings can improve thermal comfort inside the buildings owing to the induced passive air flow. Tang et al. [11] compared arc roofs with flat roofs to study why ancient architects had used arc roofs extensively (even without openings) in hot and dry regions. They noted that due to extended arc surface, vaulted roofs dissipate more heat to the outside surroundings. Lower surface temperature was obtained for arc roofs (especially at high rim angles).

Recently Rahmatmand et al. [12] studied airflow pattern around a 1:54 scale model of a real typical domed-roof building experimentally and numerically. In order to perform experimental studies, wind tunnel was designed in a way that the atmospheric boundary layer could be simulated. Therefore a more accurate flow pattern around the building could be obtained. The results of their study show that open apertures in buildings can induce air flow with acceptable discharge coefficient. Also, complex adjacent recirculation flows are visible in airflow illustrations around the dome. To establish further investigation on different geometries of arc roofs, Ntinas et al. [13] presented experimental and numerical study of different obstacle roof effect on airflow distribution. In this research averaged and instantaneous velocities are measured and predicted for various locations on the roof.

Using thick walls in the buildings is common in hot arid regions of Iran. Thick walls have been extensively used because of the high thermal capacity which can delay heat transfer to the inside of building. In this regard, Bahadori and Haghighat [14] showed that some parameters can decrease the maximum indoor temperature in hot arid regions, such as: the low ambient air and sky temperature (at night), high thermal capacity of the buildings and large air flow rate induced by the domed roofs. By decreasing in indoor air and interior walls temperature, mean radiant temperature of the interior surfaces is decreased and acceptable thermal comfort is obtained naturally in summer. They considered that moist walls can be cooled down by means of evaporation and proved that the reduced internal wall temperature remains almost constant during a day. Haghighi et al. [15] also studied natural cooling of the interior space of a one-floor stand-alone building with vaulted roof. They found that the wind velocity higher than 0.4 m/s can ventilate the air inside the building efficiently.

Review of previous studies [9–11,15] showed that temperature distribution and flow field inside and outside of a cistern have not been investigated comprehensively, especially when the windcatchers, the domed roof and the other exterior walls are exposed to solar radiation. To fill this research gap, a typical cistern (with domed roof, windcatchers and non-empty reservoir) is modeled numerically considering solar radiation.

Another research gap was identified after reviewing the literature: no experimental study had been performed to measure temperature distribution on a real case of an arc roof. Therefore, an experimental measurement is conducted to find temperature distribution on the dome roof which is also used to validate numerical calculations. Temperature distribution on the dome caused by solar radiation is very important (especially when the wind is not blowing) and affects the heat transfer to the cistern. It can cause air flow into and out of the cistern which is the driving force for ventilation. The moist air leaves the cistern and is replaced by outside dry air from the windcatchers, which increases water evaporation. Owing to such displacement, the stored water temperature decreases in the cistern, hence the water can be used at lower temperature in the hot summer months.

The cistern of interest is located in the city of Lar. Lar is a small city in the south of Iran with a hot and dry climate. It is located at approximately 54° E and 27° N. The cistern has a nonspherical dome, 17 m diameter and 10 m height, and four windcatchers which are located southward, eastward, northward and westward, surrounded by small traditional buildings and trees as shown in Fig. 1. There are specified periods during a year when the wind blows but most of the time the wind is not considerable, only local air movements are sensed. According to the local meteorological